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Aeronutronic Ford Corp, Newport Beach, Calif

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This report describes the development of a device that is capable of sampling gaseous emissions from automobiles. The device samples exhaust gases at a mass rate that is proportional to the total exhaust gas mass flow rate, which is measured using an ultrasonic vortex flowmeter. The flowmeter delivers signals, which are conditioned by process control electronics, to a sample valve. Non-standard temperature and pressure conditions at both the vortex flowmeter and the sample valve are compensated for in the process control electronics. The report focuses primarily on development of the vortex flowmeter, the sample valve, and the process control electronics. These three components comprise the heart of the proportional sampling system.

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DEVELOPMENT OF A PROPORTIONAL SAMPLER FOR AUTOMOBILE EXHAUST EMISSIONS TESTING

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ABSTRACT

This report documents the successful development of a proportional sampler for measurement of automobile exhaust mass emissions. The device dynamically maintains a sample mass flow at a constant, known fraction of the tailpipe exhaust mass flow. Neither the sample nor the exhaust is diluted in any manner. Sampling proportionality is maintained through all modes of the EPA urban driving schedule.

The proportional sampler major components are an exhaust flowmeter, sample flow control valve, electronic signal processor, sample conditioning system, and an exhaust heat exchanger. The flowmeter is a vortex-shedding type. The sample valve is a flapper valve operated in an on/off pulsed mode. The signal processor controls the valve pulse frequency to maintain sample mass proportionality.

Extensive development testing led to use of a water-to-exhaust heat exchanger upstream of the flowmeter. This provided acceptable flowmeter accuracy and satisfactory overall performance for the device, which was then delivered to EPA's Triangle Park facility. The equipment design and test results are discussed in the report.

This report was submitted in fulfillment of Contract Number 68-02-1755, by Aeronutronic Ford Corporation, under the sponsorship of the Environmental Protection Agency. Work was completed as of December 1975.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

A/D -- analog-to-digital

CL -- chemiluminescent

CVS -- constant volume sampler

CVS-CH -- cold/hot start CVS (procedure)

°C -- degree Celsius

cm -- centimeter

D/A -- digital-to-analog

DIP -- dual in-line package

FID -- flame ionization detector

Hz -- Hertz

hr -- hour

ISB -- intermediate significant bits

°K -- degree Kelvin

kgm -- kilogram

kJ -- kilojoule

kPa -- kilopascal

LFE -- laminar flow element

LSB -- least significant bits

lpm -- liter per minute

ABBREVIATIONS (Continued)

MSB -- most significant bits

m -- meter

mm -- millimeter

ms -- millisecond

NDIR -- non-dispersive infrared

ROM -- read-only memory

SAR -- successive approximation register

sec -- second

VAC -- volts, alternating current

VDC -- volts, direct current

w -- watt

μm -- micro-meter

μs -- micro-second

SYMBOLS

A_0, A_1, A_2 -- coefficients used in Equation 16

Ar -- argon

CH_Y -- fuel formula

CO -- carbon monoxide

CO_2 -- carbon dioxide

D -- duct diameter

d -- strut diameter

f -- vortex frequency

f_c -- cutoff frequency

f_m -- maximum frequency

SYMBOLS (Continued)

H -- absolute humidity

HC -- hydrocarbon

H_2O -- water

k -- proportionality constant

ℓ -- inductance tube length

M_i -- mass of ith specie emitted

m_i -- mass of ith specie in sample

N_2 -- nitrogen

NO_x -- oxides of nitrogen

O_2 -- oxygen

P_B -- barometric pressure

P_S -- standard barometric pressure

P_1 -- pressure at flowmeter

P_1' -- actual pressure at valve inlet

P_4 -- vacuum at condensate trap

Q -- volume flow rate

Q_A -- actual volume flow rate

Q_S -- standardized volume flow rate

q_m -- maximum sample flow rate

q_s -- average sample flow rate

R_T -- resistance at temperature T

SYMBOLS (Continued)

R_o -- ice-point resistance

Re -- Reynolds number

S -- Strouhal number

$(SVP)_1$ -- saturated water vapor pressure at temperature T_1

$(SVP)_4$ -- saturated water vapor pressure at temperature T_4

T -- temperature

T_1 -- temperature at flowmeter

T_2 -- temperature at valve inlet

T_s -- standard temperature

t -- time

t_c -- valve cycle interval

t_o -- valve-open interval

t_t -- test interval

U -- gas velocity

$\overline{U}$ -- average gas velocity

V -- cumulative exhaust volume

V' -- cumulative volume of dried exhaust

V_T -- plenum tank volume

v -- cumulative sample volume

X_i -- volume fraction of ith specie

X''_i -- volume fraction of ith specie in dried sample

SYMBOLS (Continued)

X''_{co} -- CO fraction in dried sample

X''_{CO_2} -- CO_2 fraction in dried sample

X_{H_2O} -- H_2O fraction in exhaust

X'_{H_2O} -- H_2O fraction in dried exhaust

X''_{H_2O} -- H_2O fraction in dried sample

Y -- fuel hydrogen/carbon ratio

α, δ -- coefficients in Equation 20

ΔQ_A -- actual exhaust volume per flowmeter pulse

ΔQ_S -- standard exhaust volume per flowmeter pulse

Δq_s -- sample volume per flowmeter pulse

Δt_m -- time interval between flowmeter pulses

λ_o -- effective/full-open sample flow ratio

λ_1 -- leakage/full-open sample flow ratio

μ -- exhaust gas viscosity

ν -- viscosity temperature exponent

ρ_i -- standard density of ith specie

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The ultimate success of the program was due primarily to the concerted efforts of the personnel within the Industrial and Environmental Products Operation of the Aeronutronic Division. In particular, Mr. R. L. Kopp was responsible for the detailed design and implementation of the signal processor electronics.

SECTION 1

INTRODUCTION

The purpose of this program was to develop and evaluate a proportional sampler for determining automobile exhaust mass emissions. The principal requirement for this device is to sample the exhaust at a mass flow rate which is a constant, known fraction of the instantaneous total exhaust mass flow rate. Unlike a constant volume sampler (CVS) the proportional sampler does not dilute the exhaust with ambient air. This can result in an order of magnitude increase in the sample concentrations, which in turn could permit quantitative identification of trace pollutants in the exhaust.

Specific design requirements were as follows:

(1) Maintain sampling proportionality throughout the standard EPA Urban Driving Schedule (LA-4-S-3, as specified in the Federal Register, Vol. 37, No. 221, dated Wednesday, November 15, 1972), including idle, acceleration, cruise, and deceleration modes.

(2) Provide a condenser and trap for removal of water and heavy hydrocarbons from the sample.

(3) Maintain the sample lines preceding the trap at a minimum of 93°C.

(4) Hold the entire volume of sample obtained from an LA-4-S-3 test in a single bag.

(5) Withstand exposure to high temperature, corrosive exhaust gases. Only 316 stainless steel or Teflon or equivalent materials shall contact the sample.

(6) Sample the exhaust at a minimum rate of one part sample per thousand parts exhaust.

(7) Provide a sample flow rate of at least six liters per minute under maximum conditions.

(8) Insure that the sample is not diluted in any manner.

(9) Display cumulative exhaust volume and instantaneous system pressures and temperatures.

(10) Provide 0.5 second response in the measurement of exhaust temperature.

Performance objectives of the device were as follows:

(1) Agreement within ±3 percent by comparison with a constant volume sampler for masses of hydrocarbon, CO, oxides of nitrogen, and CO_2 in an LA-4-S-3 test. Test-to-test repeatability of ±5 percent for these specie mass data.

(2) Exhaust flow metering accuracy (cumulative volume) of ±1 percent.

(3) Exhaust sampling rate of at least 40 Hertz under maximum conditions.

(4) Exhaust flow range capability of 10 to 850 cubic meters per hour (m^3/hr).

(5) Tailpipe pressure disturbance of 1.24 kiloPascals (KP_a) or less under maximum conditions.

(6) Achievement of performance goals for exhaust temperatures up to 450°C.

(7) Satisfactory completion of at least 8000 LA-4-S-4 tests without major component failure.

The program activities encompassed the design, manufacture, checkout, calibration, and test of the device. Engineering liaison was provided during the installation and initial evaluation testing of the device at the EPA Triangle Park facility. Operating and maintenance instructions were also provided for the device.

This Final Report documents all technical activities performed during the program. A summary of the program is provided in Section 2, including the equipment design, test results, conclusions and recommendations. Detailed discussions of the equipment design and test results are then presented in Sections 3 and 4, respectively. A detailed Requirements Specification for the proportional sampler is provided in Appendix A. Appendix B is an Evaluation Test Plan for use at the EPA Triangle Park facility.

SECTION 2

SUMMARY

EQUIPMENT DESIGN

The proportional sampler design is based upon the following basic concept. A gas flowmeter is used to measure the total dynamic exhaust mass flow from the tailpipe. A sample of the exhaust is drawn from the total flow through a sample flow control valve. Operation of this valve is regulated by signal processing electronics so as to maintain the sample flow at a constant mass fraction of the total exhaust flow. The sample flow is kept above its dewpoint using a heated line up to the inlet of a refrigerated condenser and trap. The dried sample is filtered and collected in a sample bag. As with a constant volume sampler (CVS), the sample bag then contains a mass-weighted average of the vehicle pollutant concentrations over a dynamic driving schedule.

The exhaust flowmeter selected for the proportional sampler uses the principle of vortex shedding to measure the gas volume flow rate. This type of flowmeter features good repeatability, good dynamic range, rapid response, low pressure loss, and good durability. The flowmeter consists of a duct with a small diameter rod positioned crosswise to the flow. As the flow passes the rod a stable pattern of vortices is established behind the rod. The rate (i.e., frequency) at which vortices are shed from the rod is approximately proportional to the volume flow rate of gas through the duct. The vortex shedding frequency is detected using an ultrasonic beam transmitted laterally across the duct behind and perpendicular to the rod. Each vortex scatters the ultrasonic beam, and the result is an amplitude-modulated signal. This signal is converted by flowmeter electronics into a pulse train with a frequency equal to the vortex shedding frequency.

The sample flow control valve is a solenoid driven flapper valve operated in an on/off pulsed mode. A fixed valve-open interval is used, so that the average sample flow is then (approximately) proportional to the valve pulse frequency. This approach to the valve design was selected to provide good stability and insensitivity to contamination in the sample flow metering. The valve is a modified missile control hot gas valve with exceptional durability for the proportional sampler application. The valve response is proportional to its instantaneous pulse frequency, which may be a maximum of 40 Hertz. Since the valve frequency is approximately proportional to the exhaust flow rate, the valve response to dynamic pollutant concentration variations tends to minimize distortion in the final mass-weighted-average sample.

The principal function of the signal processing electronics is to control the sample valve pulse frequency, and thereby maintain the sample mass flow at a constant fraction of the exhaust flow. This requires the signal processor to compensate for (1) flowmeter nonlinearity, (2) variable exhaust pressure and temperature, (3) variable gas temperature at the sample valve inlet, and (4) leakage through the sample valve in the valve-closed state. Secondary functions of the signal processor are to totalize the exhaust mass flow and provide system parameter output signals. The signal processor consists of a special purpose digital computer which evaluates the system equations in real-time. An absolute pressure transducer and two platinum-wire resistance temperature sensors comprise the essential instrumentation.

The complete sample flow system includes a probe, pre-filter, flow control valve, heated transfer line, refrigerated condensor, condensate trap, filter, pump, diversion valves, collection bags, purge air pump, and supplemental system pressure and temperature indicators. The proportional sampler operates on 115 VAC power. The electrical system includes DC power supplies, signal processor and sequential control electronics, pumps, valves, heated line controller, refrigeration unit, and cooling fans. The equipment is housed in a three bay console, with an externally-mounted exhaust heat exchanger.

Operation of the device is consistent with either the 1974 CVS or 1975 CVS-CH federal test procedures. An operator's control panel provides for (1) selection of exhaust flow range, (2) automatic test sequencing with selectable test intervals and optional remote start, (3) independent transfer of any sample to an analysis system, (4) selection of probe flush, condensate trap drain, or bag purge functions, (5) readout of cumulative test time, cumulative exhaust volumes, and key operating parameters, and (6) output of signal processor parameters to external recorders.

Development tests of the proportional sampler established the need for acoustic muffling and cooling of the exhaust upstream of the flowmeter. Both needs were met by using an open cycle (i.e., no water return) water-to-exhaust heat exchanger. Ambient temperature facility water is passed in counterflow through a cooling coil assembly mounted inside an exhaust plenum tank. The plenum tank, besides housing the heat exchanger, acts as a low-pass acoustic filter against tailpipe pressure fluctuations. To maintain the proper time-phase relation between the exhaust and sample flows, the sample probe is located upstream of the plenum tank. In this configuration the transport delay of exhaust from the tailpipe to the sample probe is minimized, while the delay in flowmeter response to exhaust flow rate changes remains negligible.

TEST RESULTS

Testing activities during the program included (1) development and calibration of the exhaust flowmeter, (2) development and calibration of the sample flow control valve, (3) development of the proportional sampler configuration, and (4) evaluation of the final device configuration. The results of these tests are summarized below.

The exhaust flowmeter was developed and initially calibrated by the supplier, J-Tec Associates. The flowmeter configuration was similar to that tested in an earlier program (Reference 1) involving direct measurement of automobile exhaust flow. The supplier's calibration data, using a laminar flow element (LFE) as the reference, indicated satisfactory operation over the flow range from 10 cubic meters per hour (m^3/hr) up to over 850 m^3/hr. The calibration was independently verified at Aeronutronic using three LFE's over the range of 10 to 586 m^3/hr. As expected, the flowmeter signal is significantly nonlinear at flow rates below 50 m^3/hr. This nonlinearity is compensated for by the signal processor.

Development of the sample flow control valve principally involved minimizing the leakage flow in the valve-closed position. A maximum leakage limit of three percent of full-open flow could not be achieved with the original flapper/orifice design. A small stainless steel ball was used in a modified orifice design to compensate for flapper/orifice misalignment. This approach was successful in reducing the leakage flow to one-half percent of full-open flow. The valve was then flow calibrated using a differential weight technique. Valve flow was found to be linear up to 40 Hertz pulse rate, with a flow rating of 8.5 liters per minute (lpm) at 40 Hz.

Development testing of the proportional sampler was conducted in two phases. All testing was done in the Aeronutronic Emissions Test Cell. Vehicles with engines from 2.3 liter (4 cylinder) up to 6.6 liter (V-8) were used in both steady-speed and dynamic cycles on a chassis dynamometer. A CVS was used in series (downstream) with the proportional sampler so that the two measurements of vehicle CO_2, CO, NO_x, and HC mass emissions could be compared for each test.

The first phase of development testing involved principally the exhaust flowmeter. Initial tests showed large (30-50 percent low) errors in the flowmeter output. Monitoring of the flowmeter internal electronic signals revealed a severe interference in the vortex detection process, which in turn led to loss of output signal pulses. Additional diagnostic testing indicated the presence of acoustic noise in the flowmeter duct at frequencies within the pass band of the vortex-shedding process. This suggested the use of a plenum volume upstream of the flowmeter to filter the acoustic disturbance. An experiment with two 208 liter drums connected in series was successful in drastically improving the flowmeter signal quality. This, along with minor adjustments in the flowmeter electronics, resulted in good agreement between the flowmeter and the CVS in tests using the

EPA urban driving schedule. Further testing and analysis led to the design of a 237 liter tank to be installed between the sample probe and the flowmeter.

The second phase of development testing was conducted after completion of the proportional sampler assembly, including the external plenum tank, but prior to development and installation of the exhaust heat exchanger. Initial tests of this configuration showed poor flowmeter signal quality and consequent errors in the measured mass emissions. These appeared to be caused by a flowmeter malfunction and by resonant acoustic waves in the ducting. Repair of the flowmeter improved the signal, but did not wholly account for the excessive output signal error. Attempts to attenuate the acoustic resonance conditions in the plenum tank led to the discovery that the flowmeter error varied with the exhaust gas temperature at the flowmeter. Tests with heated ambient air showed that the flowmeter signal quality deteriorated rapidly for gas temperatures above 65°C. An experimental heat exchanger was then tested with vehicle exhaust. By reducing the gas temperature from over 200°C to below 50°C the flowmeter signal error was eliminated. A permanent exhaust heat exchanger was then designed, fabricated, and installed inside the plenum tank.

Final testing of the proportional sampler at Aeronutronic demonstrated the adequacy of the exchanger performance, flowmeter signal quality, and CO_2 mass emissions comparisons with the CVS. The equipment was then delivered to the EPA Triangle Park facility for evaluation testing and acceptance. Initial testing at this facility indicated generally satisfactory performance of the device, even for vehicles equipped with oxidation catalysts and producing exhaust temperatures up to 450°C.

CONCLUSIONS

This program has resulted in the successful development of a proportional sampler for characterization of automobile exhaust mass emissions. The equipment design requirements and performance objectives were satisfied, subject to the following limitations:

(1) Additional evaluation testing is required to more firmly establish the accuracy and repeatability of the device for the primary species of CO_2, CO, NO_x, and total hydrocarbons.

(2) Achievement of an accurate exhaust flowmeter signal requires substantial cooling of the exhaust gas and attenuation of acoustic noise from the tailpipe. This typically results in condensation of water vapor from the exhaust flow, which could complicate interpretation of mass emissions measurements.

(3) For larger engines, the additional pressure loss through the exhaust heat exchanger can induce a tailpipe backpressure disturbance in excess of 1.24 kPa. However, excursions above this limit occur only momentarily during peak vehicle accelerations (typically once during the EPA urban driving schedule).

(4) The exhaust flowmeter, as finally configured, has an upper limit of 500 m^3/hr for accurate operation. This limitation is unimportant for even the largest engines used in light duty vehicles.

(5) The response of the exhaust temperature sensor generally exceeds 0.5 second, but is adequate due to the large thermal inertia of the exhaust heat exchanger.

RECOMMENDATIONS

The following general recommendations are offered for the use and possible further development of the proportional sampler:

(1) The accuracy and repeatability of the device should be firmly established using comparisons of CO_2 and CO mass emissions between the proportional sampler and a CVS in series.

(2) Comparisons of CO_2 and CO mass emissions between the proportional sampler and a CVS should be used as experimental controls for all testing with the device.

(3) It may be desireable to modify the sample flow system to improve the sample integrity for some pollutants of interest. Modifications could include using a higher temperature heated line, bypass of the condenser and trap, or the use of special filter media. These would be subject to the limitation that the sample flow remain choked across the sample flow control valve orifice.

(4) Future versions of the proportional sampler could employ several design improvements, including a simplified flowmeter configuration, a signal processor with reduced self-test capability, a membrane sample dryer in place of the refrigerated condenser and trap, a simplified heat exchanger assembly with reduced exhaust pressure loss, a closed cycle exhaust temperature control system, and more compact packaging of the equipment.

SECTION 3

EQUIPMENT DESIGN

The design rationale for the proportional sampler and its principal components are presented in this section. A general discussion of the device's theory of operation, fluid system, electrical system, console layout, and operating characteristics is provided first. This is followed by more detailed discussions of the exhaust flowmeter, sample flow control valve, signal processor, and exhaust heat exchanger.

GENERAL

Theory of Operation

The following equations describe the essential characteristics of the exhaust flowmeter, sample flow control valve, the valve control problem, and exhaust emissions calculations.

The exhaust flowmeter provides a direct measurement of gas volume flow rate. The gas absolute pressure and temperature must be measured at the flowmeter to convert the volume flow rate into a mass flow rate (i.e., volume flow rate at standard pressure and temperature). The equation is:

$$Q_s = Q_A P_1 T_s/(P_s T_1) \qquad (1)$$

where Q_s = exhaust standardized volume flow rate (m^3/hr at 20°C and 101.325 kPa).

Q_A = exhaust actual volume flow rate (m^3/hr).

P_1 = exhaust gas pressure at the flowmeter (kPa, absolute).

P_s = standard pressure (= 101.325 kPa).

T_1 = exhaust gas temperature at the flowmeter (°K).

T_s = standard temperature (= 20°C = 293.15°K).

The sample flow control valve operates in an on/off pulsed mode. A sample pump downstream of the sample valve provides sufficient vacuum at the valve outlet to maintain choked (i.e., critical) flow across the valve orifice. During the valve-open portion of a complete valve cycle the sample flows at its maximum rate. During the valve-closed part of the cycle the nominal flow is zero. Two non-ideal effects must also be considered. First, the valve leaks slightly in the valve-closed position. Second, the transient flows during the opening and closing transitions may not exactly balance out. The result is the following general equation for the average sample flow over a complete valve cycle:

$$q_s = q_m \frac{P_1'}{P_s} \sqrt{\frac{T_s}{T_2}} \left[\frac{\lambda_o\ t_o + \lambda_1\ (t_c - t_o)}{t_c} \right] \qquad (2)$$

where q_s = average sample standardized volume flow rate (liters per minute at 20°C and 101.325 kPa).

q_m = sample standardized volume flow rate for the full-open valve (lpm at 20°C and 101.325 kPa valve inlet conditions).

P_1' = actual valve inlet pressure (kPa, absolute).

T_2 = actual valve inlet gas temperature (°K).

λ_o = ratio of effective/full-open sample flow during valve-open interval.

λ_1 = ratio of leakage/full-open sample flow during valve-closed interval.

t_o = valve-open interval (sec).

t_c = valve cycle interval (sec).

= valve-open interval plus valve-closed interval.

The signal processor must then turn the sample valve on and off (i.e., open and closed) to maintain the relationship:

$$q_s = k\ Q_s/60 \qquad (3)$$

where k = sample proportionality constant (parts per thousand).

Combining these equations yields the following expression for the valve cycle interval (assuming equivalent flowmeter and valve inlet pressures):

$$t_c = \frac{t_o\ (\lambda_o - \lambda_1)}{\left(\frac{Q_A}{q_m} \cdot \frac{k}{60} \cdot \frac{T_s}{T_1} \cdot \sqrt{\frac{T_2}{T_s}} - \lambda_1\right)} \tag{4}$$

By using a fixed valve-open interval, the dynamic variables in Equation 4 are limited to Q_A, T_1 and T_2.

The use of this sample valve technique implies discrete rather than continuous sampling of the exhaust. The possible distortion this might create in the sample can be evaluated using the general sampling theorem of modern communication theory (Reference 2). This states that any $2 \times f_m$ independent, discrete samples per second are sufficient to characterize a function varying at a maximum frequency of f_m cycles per second. In the proportional sampler application, if the exhaust specie concentrations vary at a frequency of one cycle per second, the required valve pulse rate for a distortion-free sample would be two cycles per second. The upper limit for the valve pulse rate is determined by the need to provide a constant value of λ_o independent of the value of t_c. Valve calibration data will show that for $t_c \geq 0.025$ sec this constraint is met. Thus the valve can be cycled at frequencies up to 40 Hz, for an equivalent specie concentration bandwidth of 20 Hz. This maximum valve pulse rate can be employed for any given test by selection of the appropriate peak vehicle exhaust flow rate. This "range change" capability is provided in the signal processor and is equivalent to selecting the proportionality constant, k.

The above equations do not account for removal of water vapor from either the sample or the main exhaust flow. In the final equipment configuration both flows will be substantially dried. Assuming that no species to be measured are lost in the condensation processes, correction for water removal requires only adjustments for the decrease in gas volume in the sample collection bag and in the exhaust flow at the flowmeter. These corrections are applied in the final calculations of pollutant mass emissions, as described below.

The proportional sampler may be used to determine mass emissions in two ways. First, the pollutant concentrations in the collection bag may be measured using a separate analysis system. The pollutant mass for a given test is then:

$$M_i = \rho_i X_i V \tag{5}$$

where M_i = mass of ith specie emitted (grams).

ρ_i = density of ith specie at standard temperature and pressure (gm/m^3).

X_i = volume fraction of ith specie in the exhaust, averaged over the test.

V = cumulative exhaust standardized volume over the test (m^3).

Typically the exhaust heat exchanger will remove most of the water vapor in the original exhaust. The signal processor provides for accumulation of the temperature- and pressure-corrected flowmeter signal as follows:

$$V' = \int_0^{t_t} \frac{Q_s}{3600} (dt) \qquad (6)$$

where V' = cumulative dried exhaust standardized volume over the test (m^3).

t_t = test interval (sec).

Since only water vapor is (partially) removed, the metered volume will differ from the original exhaust volume by the factor:

$$V' = V (1 - X_{H_2O})/(1 - X'_{H_2O}) \qquad (7)$$

where X'_{H_2O} = volume fraction of water vapor in the exhaust gas at the flowmeter.

X_{H_2O} = volume fraction of water vapor in the original exhaust.

The partially dried sample will also experience a volume decrease, with the following effect on measured specie concentrations:

$$X''_i = X_i (1 - X''_{H_2O})/(1 - X_{H_2O}) \qquad (8)$$

where X''_i = volume fraction of ith specie in the dried sample, averaged over the test.

X''_{H_2O} = volume fraction of water vapor in the dried sample

Equations 7 and 8 may be used with Equation 5 to determine the final pollutant mass emissions:

$$M_i = \rho_i X''_i V' (1 - X'_{H_2O})/(1 - X''_{H_2O}) \qquad (9)$$

The two water vapor fractions required in the evaluation of Equation 9 may be estimated using the following expressions:

$$X'_{H_2O} = (SVP)_1/P_B \qquad (10)$$

$$X''_{H_2O} = (SVP)_4/(P_B - P_4) \qquad (11)$$

where $(SVP)_1$ = saturated water vapor pressure at temperature T_1 (kPa).

$(SVP)_4$ = saturated water vapor pressure at the refrigerated condensate trap temperature, T4 (kPa).

P_B = local barometric pressure (kPa, absolute).

P_4 = vacuum reading at the condensate trap (kPa, vacuum gage).

In evaluating Equations 10 and 11, the assumption of average parameter values is sufficiently accurate for normal testing. Note that estimation of the water vapor fraction in the original exhaust is not required for this type of mass emissions measurement.

The second method of determining mass emissions is to directly measure the mass of pollutant contained in the sample flow extracted from the total exhaust over the test interval. This could be done by filtering the sample flow with specie-selective traps, and measuring the mass of each collected specie, m_i. This is equivalent to measurement of the specie volume fractions and the cumulative sample standardized volume:

$$m_i = \rho_i X_i v \qquad (12)$$

where $$v = \int_0^{t_t} \frac{q_s}{60,000} (dt) \qquad (13)$$

and where v = cumulative (undried) sample standardized volume over the test (m^3)

Then Equations 3, 6, 7, 12 and 13 may be combined to yield the relation:

$$m_i = \rho_i X_i V \frac{k}{1000} \frac{(1 - X_{H_2O})}{(1 - X'_{H_2O})} \qquad (14)$$

Finally, Equation 5 is employed in rearranging Equation 14 to yield the following result for the total mass of the ith specie:

$$M_i = m_i \frac{1000}{k} \cdot \frac{(1 - X'_{H_2O})}{(1 - X_{H_2O})} \qquad (15)$$

The proportionality constant, k is known from the sample valve calibration data. The water vapor correction factor in Equation 15 may be estimated using the following expression:

$$\frac{(1 - X'_{H_2O})}{(1 - X_{H_2O})} = A_o + A_1 X''_{CO_2} + A_2 X''_{CO} \qquad (16)$$

with the coefficients defined as:

$$A_o = (1 - X'_{H_2O}) (1 + 0.23 H)$$

$$A_1 = 0.5y (1 + 0.115 H) \frac{(1 - X'_{H_2O})}{(1 - X''_{H_2O})}$$

$$A_2 = [0.5y - (0.5 - 0.25y) 0.23 H] \frac{(1 - X'_{H_2O})}{(1 - X''_{H_2O})}$$

and where H = ambient air absolute humidity (gm water per kgm of dry air).

y = hydrogen/carbon atomic ratio in test fuel.

X''_{CO_2} = volume fraction of CO_2 in dried sample, averaged over the test.

X''_{CO} = volume fraction of CO in dried sample, averaged over the test.

Equation 16 is derived assuming combustion of fuel to CO_2, CO, and H_2O at air/fuel ratios greater than stoichiometric. Note that measurement of ambient humidity is a standard requirement in most emissions test facilities.

Fluid System

The proportional sampler fluid system is illustrated schematically in Figure 1. The system consists of three principal flow networks -- main exhaust, sample, and purge air. These are described below.

Main Exhaust Flow - The vehicle or engine exhaust first passes through an inlet duct where the sample is extracted. The exhaust then enters the external heat exchanger, passing across a column of cooling coils and out through a return duct to the flowmeter. The design of these major components of the fluid system is presented in subsequent paragraphs.

One temperature and three pressure measurements are provided in the exhaust ducting. First, at the sampler inlet, is a low-range pressure gage. This gage is mounted on the lower front panel, and provides a dynamic measurement of exhaust backpressure for visual monitoring only. An absolute pressure transducer is mounted on the flowmeter tube to measure the gas pressure P_1. This transducer is the strain-gage diaphragm type and its signal is input to the signal processor. The gas temperature at the flowmeter, T_1, is measured using a platimum-wire resistance temperature sensor. This probe is mounted in the exit duct just downstream of the flowmeter. As with the P_1 transducer, the T_1 probe interfaces electrically with the signal processor. Either signal may be visually monitored using a meter on the operator's control panel.

Sample Flow - The exhaust sample train includes the probe, prefilter, sample flow control valve, heated line, refrigerated water bath and condensate trap, sample filter, vacuum adjustment valve, sample pump, bag input solenoid valves, sample collection bags, and bag output valves. The principle features of these components are noted below.

The sample probe is located in the inlet duct. The probe rises vertically to the prefilter. The prefilter has a stainless housing and element with Teflon seals. The probe orientation and prefilter are intended to minimize the entrainment of particulates in the sample flow. A variety of elements may be used in the prefilter. The minimal filtration level is 40 to 50 μm, with an approximate pressure drop of 0.25 kPa at the maximum sample flow rate.

The design of the sample flow control valve is reviewed separately in a subsequent paragraph.

The sample line from the sample valve outlet to the condenser coil in the refrigerated water bath is temperature-controlled up to 93°C. The line is 4.7mm inside diameter Teflon traced with electrical heating wire, thermal insulation and a protective casing. The heating wire extends around the base of the sample valve, around the valve inlet tubing, and around the sample probe down to the fitting on the main inlet duct. Separate pieces of thermal insulation and protective casing are clamped to these segments. The heated line junction box is located at the inlet

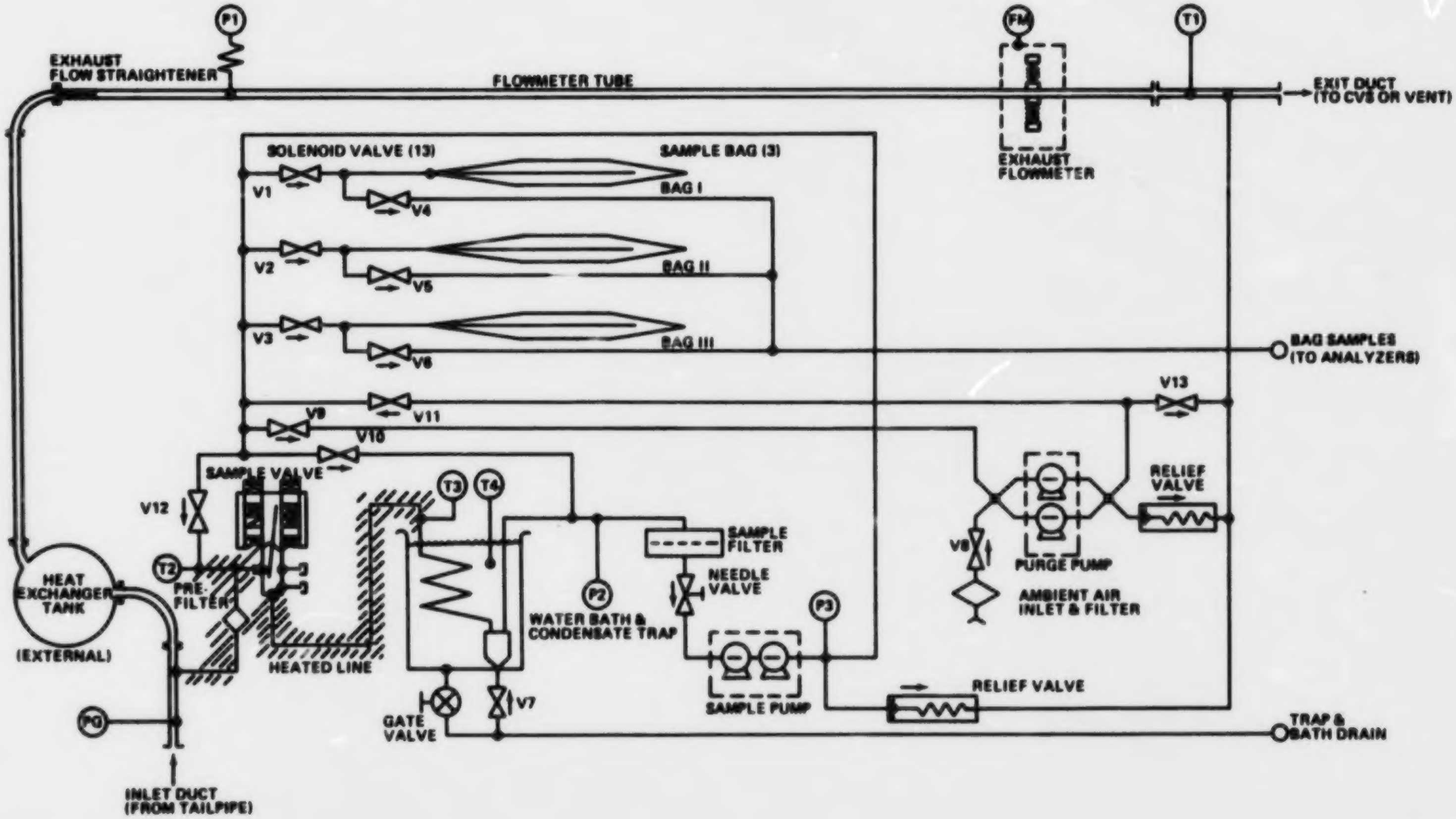

P1
EXHAUST FLOW STRAIGHTENER
FLOWMETER TUBE
FM
T1
EXIT DUCT (TO CVS OR VENT)
EXHAUST FLOWMETER
SOLENOID VALVE (13)
SAMPLE BAG (3)
V1
V4
BAG I
V2
V5
BAG II
V3
V6
BAG III
BAG SAMPLES (TO ANALYZERS)
V9
V11
V13
V10
SAMPLE VALVE
V12
T3
T4
RELIEF VALVE
SAMPLE FILTER
HEAT EXCHANGER TANK
(EXTERNAL)
T2
PRE-FILTER
NEEDLE VALVE
V8
PURGE PUMP
AMBIENT AIR INLET & FILTER
P2
WATER BATH & CONDENSATE TRAP
P3
HEATED LINE
SAMPLE PUMP
RELIEF VALVE
GATE VALVE
V7
TRAP & BATH DRAIN
P0
INLET DUCT (FROM TAILPIPE)

Figure 1. Proportional sampler fluid system schematic

to the condenser coil. The junction box houses the line temperature sensor (a thermistor capsule) and lead wire/heating wire connections.

The refrigerated water bath assembly consists of the water tank, refrigeration condensing unit, refrigeration evaporator coil, temperature control switch, sample gas condenser coil, water trap assembly, submersible pump assembly, and water tank cover.

The water bath assembly condenses water vapor from the sample gas stream, collects the water droplets, and provides a means of removing the condensed water from the console system. The sample gas is passed through the condenser coil and water trap. The coil and trap are immersed in the refrigerated water bath. Since the water temperature in the bath is maintained at 2 ±1°C, water vapor in the sample gas stream condenses, forming droplets on the inner walls of the condenser coil. The droplets are moved by gravity and the influence of the moving gas stream to the water trap assembly.

The water trap assembly separates the water droplets from the gas stream. A 50 cm^3 storage reservoir stores the condensed water. Level sensing probes indicate when the trap is 3/4 full and completely full of water. Separation of the water droplets is achieved by means of a spiral diffuser in the upper part of the trap assembly. The diffuser imparts an outward vortex motion to the gas stream. The diffuser is designed so that the droplets are blown onto the inner vertical cylindrical surface of the trap reservoir. The water droplets run down the wall, into the bottom of the reservoir. The collected pool of liquid in the reservoir rotates under the influence of the swirling gas stream. This rotation keeps the top surface of the liquid pool flat and thus prevents splashing. Splashing of the surface would cause droplets to be picked up by the gas which exits at the center, top of the trap assembly. Further protection against droplet pickup in the exit gas stream is provided by the outlet baffle.

The condensate water level probes are fabricated of single strand pure nickel wire. They are arranged so that the liquid level will contact one pair at the 3/4 full point and the other pair when the trap is full. The probes are electrically insulated and are unaffected by water droplet formation or the bath water.

The final sample filter is a clamshell style which uses 7 cm diameter filter papers. The filter is plumbed so that the contaminated side of the element is visible when the filter is open. For general testing Whatman grade GFC or GFA glass fiber filter papers should be used.

A needle valve is used between the filter and sample pump to control the vacuum at the condensate trap during test. The valve is adjusted to achieve a vacuum of 40 kPa at the maximum sample flow of 8.5 lpm. A higher vacuum than this could result in an above ambient dewpoint for the sample leaving the condensate trap.

The sample pump is a two-headed diaphragm type with a 250 w split-phase motor. The internal surfaces of the pump are teflon coated. The two pumping chambers are plumbed in series. This pump is identical to the purge pump. The sample pump relief valve is set to crack at 35 kPa.

Valves V1 through V6 control the flow into and out of the sample collection bags in accordance with the three test phases. These valves, as well as the condensate trap drain valve V7, are identical normally-closed solenoid valve with 4.7mm orifices and viton seals. The valves are rated for continuous duty on 24-28 VDC and will open against a maximum inlet pressure differential of 689 kPa. The diversion valve logic is summarized in Table 1.

The three sample bags are fabricated from clear Tedlar material. The edges are double heat-sealed. A 9.5mm diameter stainless distribution tube is inserted diagonally into the bag to avoid stratification of the sample gas. The bags are hung from support tubes mounted on the top of the console. The distribution tubes are cantilevered from bulkhead fittings on the internal structure.

The sample line instrumentation includes the following:

(1) Sample valve inlet temperature, T2, measured using a platinum-wire resistance temperature sensor (identical to T1 probe) mounted in the sample valve inlet tube (horizontal orientation). The probe excitation, signal conditioning, and readout are included in the signal processing electronics.

(2) Heated line temperature, T3, measured using a thermistor probe mounted inside the heated line junction box. Readout of T3 is accomplished indirectly through the temperature controller mounted on the console front panel.

(3) Refrigerated water bath temperature, T4, measured using a liquid-expansion thermometer. The probe is immersed in the water bath with a remote dial mounted on the control panel for visual monitoring.

(4) Sample line vacuum/pressure, P2, measured using a compound bourdon-tube gage mounted on the control panel.

(5) Sample manifold vacuum/pressure, P3, measured using a compound bourdon-tube gage mounted on the control panel.

Purge Air Flow - Four purge functions are provided to (1) backflush the pre-filter and sample probe, (2) drain the condensate trap, (3) fill the sample bags, and (4) evacuate the sample bags to complete the bag rinse

Table 1. SAMPLE DIVERSION AND PURGE VALVE LOGIC

	Valve												
Function	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
Test Phase I	X												
Test Phase II		X											
Test Phase III			X										
Analyze Bag I				X									
Analyze Bag II					X								
Analyze Bag III						X							
Probe Flush							X	X			X	X	
Trap Drain							X	X		X	X		
Bag Fill	X	X	X					X			X		
Bag Evacuate	X	X	X						X				X

cycle. Ambient air is used as the purge gas. The air is drawn from the console interior through a filter and moisture separator. The purge air is pumped by a two-headed diaphragm pump (identical to sample pump) plumbed with the chambers in parallel. The purge flow control valves, V8 through V13, are identical normally-closed solenoid valves with 9.5mm orifices. The valves are rated for continuous duty on 24 to 28 VDC and will open against a maximum inlet pressure differential of 13.8 kPa. Since the purge pump develops pressures greater than this the purge functions must be implemented with the sample lines vented to ambient prior to initiating the desired function. The purge pump relief valve is set to crack at 35 kPa. The trap drain valve, identical to the sample diversion valves, is oriented in a reverse flow direction to prevent leakage from ambient into the sample line during test when the trap is under vacuum. The purge valve logic is summarized in Table 1.

Electrical System

The proportional sampler electrical system is diagrammed in Figure 2. The power distribution and general electrical functions of the console are reviewed below. A detailed discussion of the signal processor design is reserved for a subsequent paragraph.

The console operates on two 115 VAC, 60 Hz, single phase power inputs, each with a maximum current of 15 amps. Facility power is routed into the relay and fuse box (lower right, rear of console) through circuit breakers. The two primary distribution lines and a power control line are each separately fused. The console power switch energizes a two-pole power control relay (K1). One primary power line serves the sample pump, purge pump, and refrigerated water bath. The other primary power line serves the electronics and valves' power supplies, exhaust flowmeter, heated sample line and cooling fans.

Four DC power supplies (lower, right, front of console) are used. The +5 VDC power is distributed within the electronics assembly for the transistor-transistor logic. The ±15 VDC supply is used for analog input and output signal conditioning and excitation. The +28 VDC supply is used for the solenoid valves and relays (K2, K3, K4). The +10 VDC supply is used in series with the +28 VDC supply to provide +38 VDC to the coils of the sample flow control valves. The supplies are all adjustable and are short-circuit protected.

The sample flow control valve operates on +38 VDC to two opposing electromagnets. Dropping resistors are used in series with the coils to limit the steady-state current. Solid-state coil drivers are used, under control of the signal processor logic, to energize one or the other coil (never both). The coils are energized only when the "Sample Valve Power" switch is closed. This switch also energizes relay K2 to turn on the sample valve cooling fan.

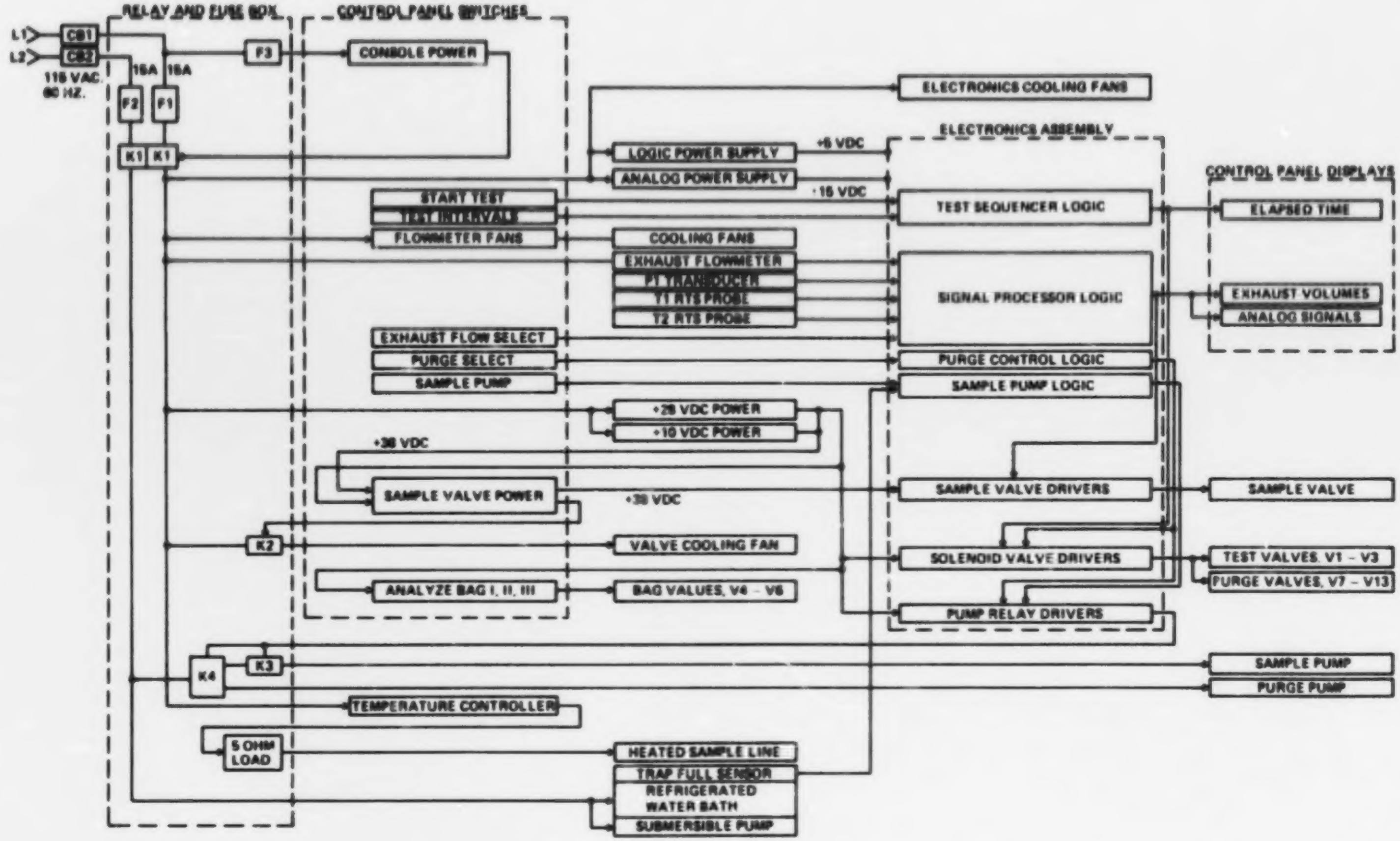

L1
L2
CB1
CB2
115 VAC.
60 HZ.
RELAY AND FUSE BOX
15A
15A
F2
F1
F3
K1
K1
K2
K3
K4
5 OHM LOAD
CONTROL PANEL SWITCHES
CONSOLE POWER
START TEST
TEST INTERVALS
FLOWMETER FANS
EXHAUST FLOW SELECT
PURGE SELECT
SAMPLE PUMP
+38 VDC
SAMPLE VALVE POWER
+38 VDC
ANALYZE BAG I, II, III
TEMPERATURE CONTROLLER
ELECTRONICS COOLING FANS
LOGIC POWER SUPPLY
ANALOG POWER SUPPLY
+5 VDC
±15 VDC
COOLING FANS
EXHAUST FLOWMETER
P1 TRANSDUCER
T1 RTS PROBE
T2 RTS PROBE
+28 VDC POWER
+10 VDC POWER
VALVE COOLING FAN
BAG VALUES, V4 – V6
HEATED SAMPLE LINE
TRAP FULL SENSOR
REFRIGERATED WATER BATH
SUBMERSIBLE PUMP
ELECTRONICS ASSEMBLY
TEST SEQUENCER LOGIC
SIGNAL PROCESSOR LOGIC
PURGE CONTROL LOGIC
SAMPLE PUMP LOGIC
SAMPLE VALVE DRIVERS
SOLENOID VALVE DRIVERS
PUMP RELAY DRIVERS
CONTROL PANEL DISPLAYS
ELAPSED TIME
EXHAUST VOLUMES
ANALOG SIGNALS
SAMPLE VALVE
TEST VALVES, V1 – V3
PURGE VALVES, V7 – V13
SAMPLE PUMP
PURGE PUMP

Figure 2. Proportional sampler electrical system diagram

The sample pump and purge pump use a common 115 VAC line controlled through relays K3 and K4. The 115 VAC input to K3 is through the normally-closed contact of K4. Thus when K4 is energized, the purge pump is turned on and the sample pump is turned off independent of whether K3 is energized or not. The purge pump is turned on through K4 by the purge pump logic whenever one of the four purge functions is selected at the operators control panel. The sample pump is turned on through K3 by the sample pump logic when the "Sample Pump" switch is closed. The sample pump logic will de-energize K3 if a trap-full indication is received from the condensate trap full sensor. Thus, the sample pump is protected from ingesting water from a full trap. Water in the pumping chambers could damage the pump due to overpressurization.

The heated sample line receives 115 VAC power through a temperature controller mounted on the console front panel. The controller uses a solid-state Triac device to regulate the load voltage. A 5 ohm load resistance (relay and fuse box) is used in series with the heated line to obtain the minimum load for stable control. An adjustable current limit is provided with the controller. A thermistor is used to sense line temperature. The load voltage is then controlled in proportion to the set point versus sensor temperature difference.

The water bath refrigeration unit is thermostatically controlled with an adjustable switch. The switch is set to the desired temperature (about 2°C). When the cooling water rises above the set temperature, the switch closes and turns on the compressor to circulate the refrigerant. The submersible pump in the water bath runs continuously. The trap-full sensor within the condensate trap is electrically isolated from the assembly.

Five cooling fans are used in the console to circulate ambient air. Two fans are located above the electronics assembly (top, right, front of console) and run whenever console power is on. Two fans are located on the console floor by the exhaust flowmeter transmitter and receiver crystals. These are turned on by an independent control panel switch. The fifth fan is used to cool the sample valve electromagnets (lower, left, front of console) and is on whenever the sample valve power switch is closed.

Console Layout

The physical construction of the proportional sampler is illustrated in Figures 3 through 7. The overall dimensions of the console are 234 cm wide by 91.5 cm deep by 206 cm high, including the heat exchanger tank.

The exhaust enters the front of the console at the lower left. After passing the sample probe, the exhaust is ducted into the heat exchanger tank. It leaves the tank near the top and is returned to the console through a vertical duct. The main flowmeter duct passes across the lower rear of the console and exits at the right side.

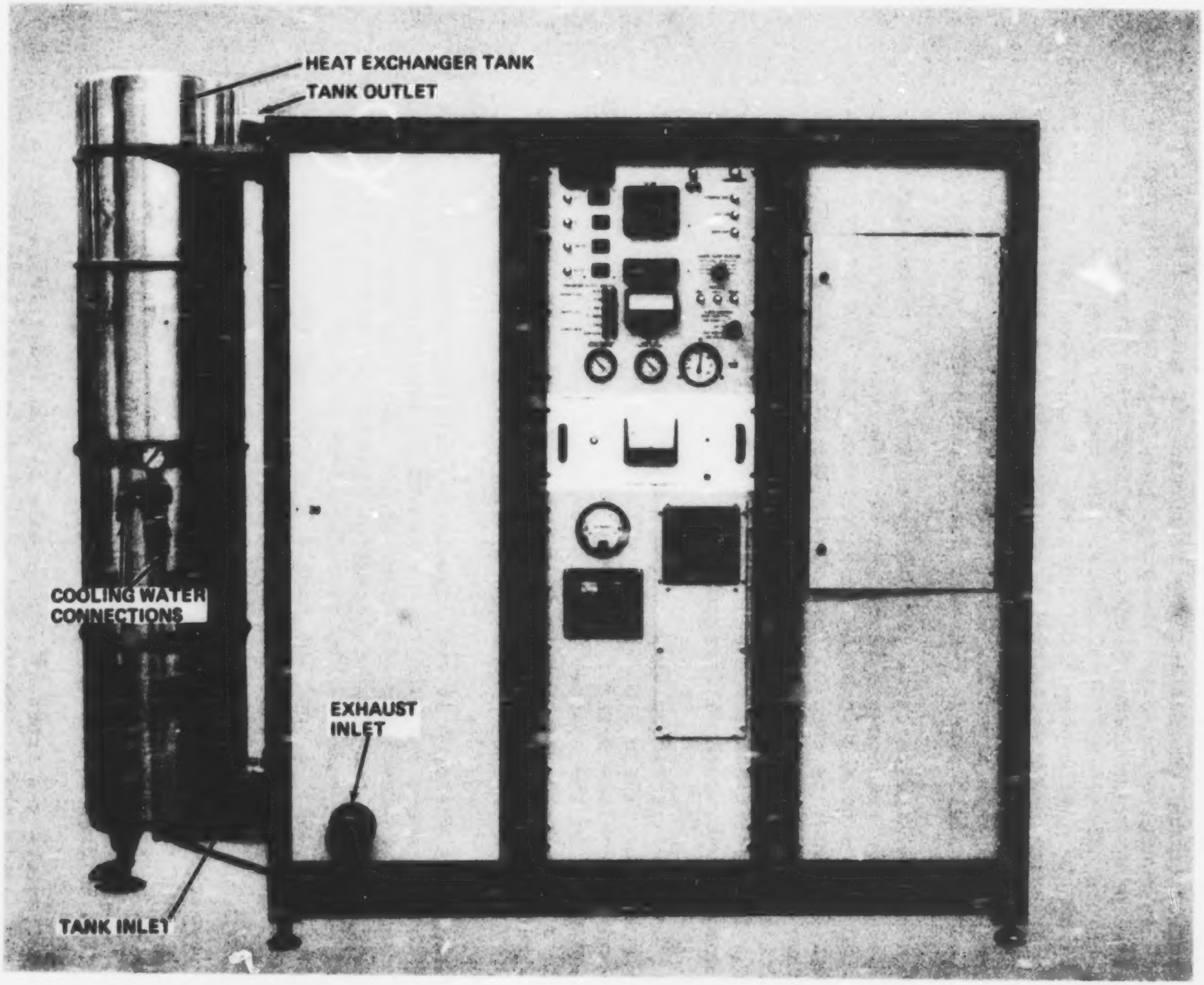

HEAT EXCHANGER TANK
TANK OUTLET
COOLING WATER CONNECTIONS
EXHAUST INLET
TANK INLET

Figure 3. Proportional sampler console (front view)

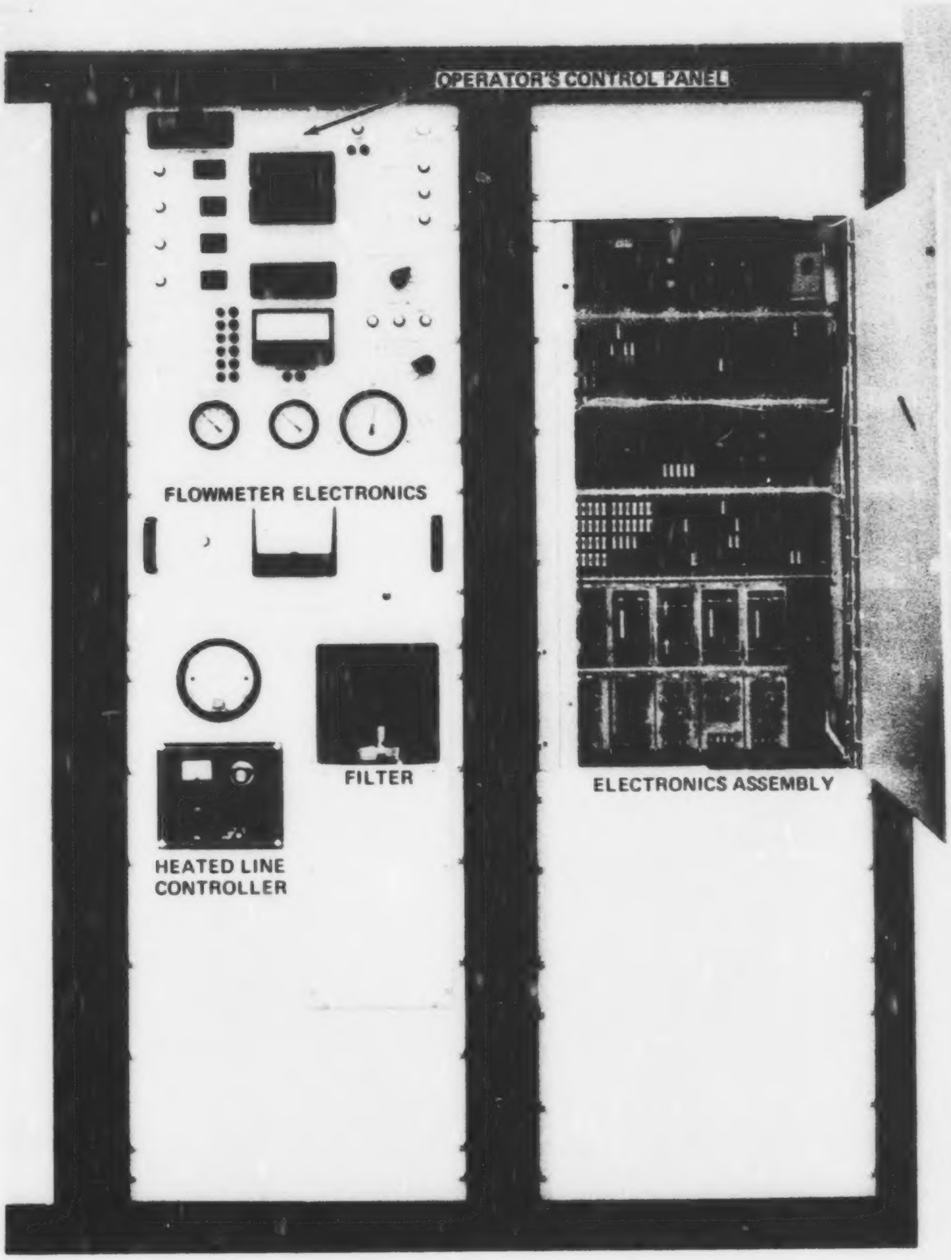

OPERATOR'S CONTROL PANEL
FLOWMETER ELECTRONICS
FILTER
HEATED LINE CONTROLLER
ELECTRONICS ASSEMBLY

Figure 4. Control panel and electronics assembly

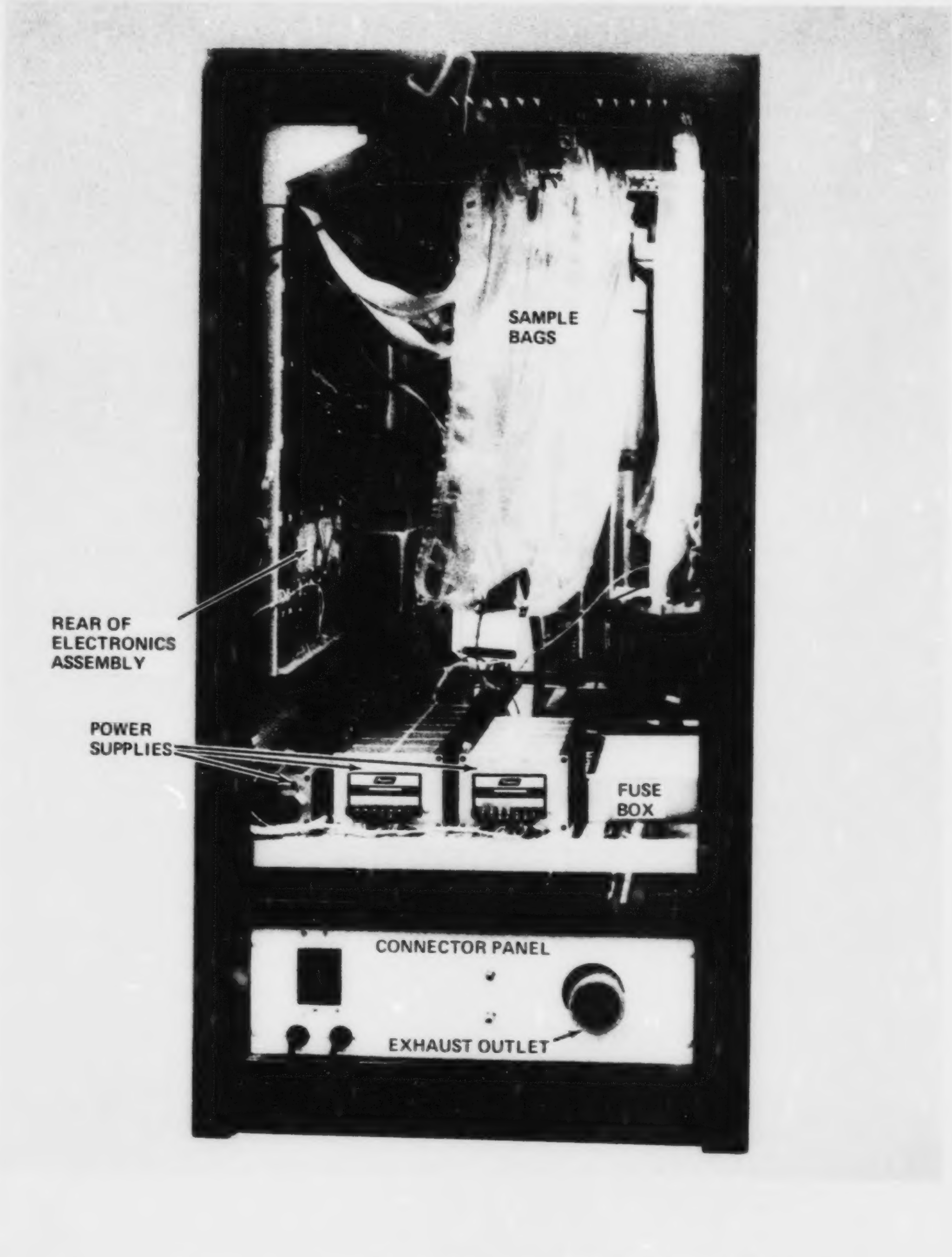

SAMPLE BAGS
REAR OF ELECTRONICS ASSEMBLY
POWER SUPPLIES
FUSE BOX
CONNECTOR PANEL
EXHAUST OUTLET

Figure 5. Console interior (right side view)

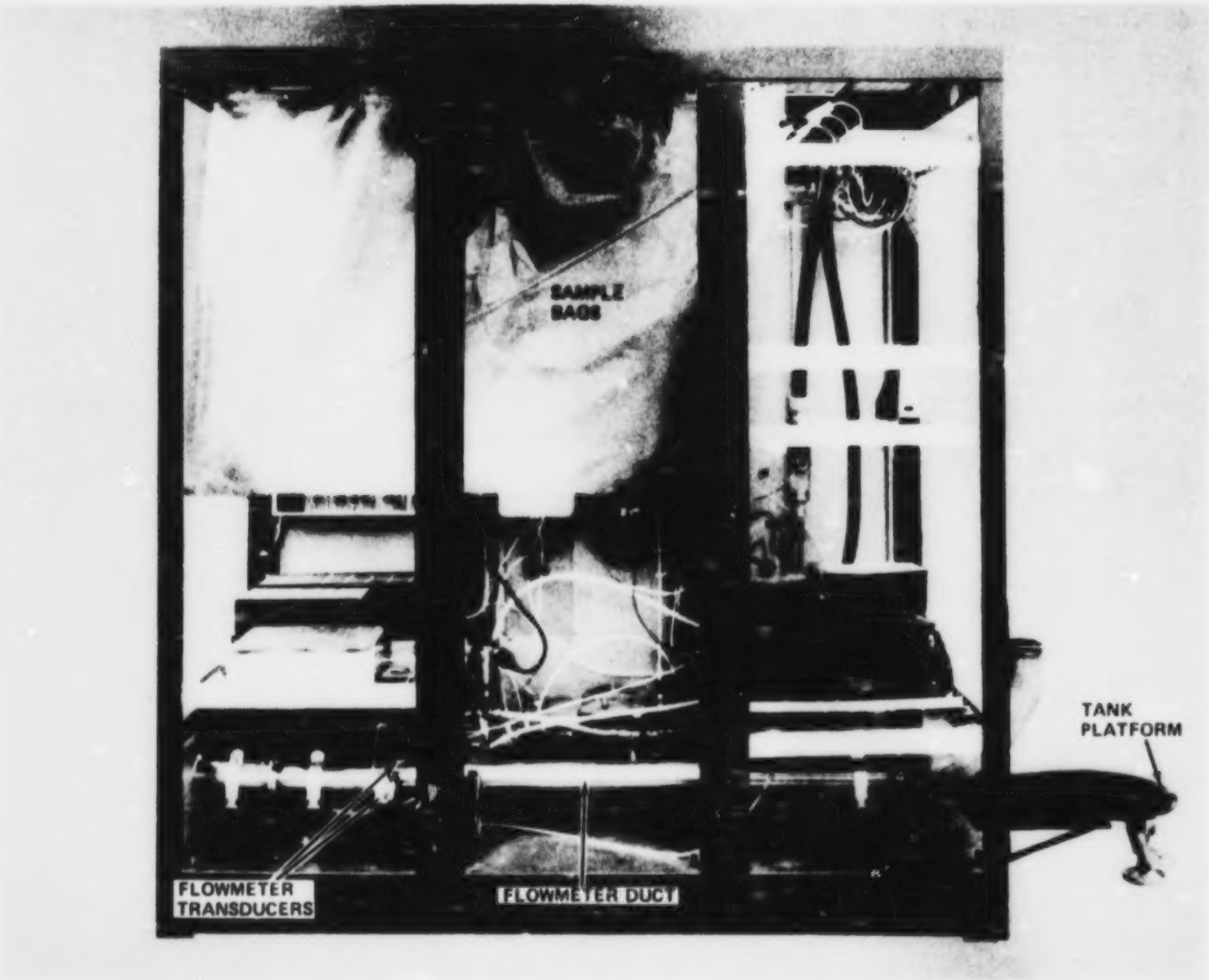

SAMPLE BAGS
TANK PLATFORM
FLOWMETER TRANSDUCERS
FLOWMETER DUCT

Figure 6. Console interior (rear view, with heat exchanger removed)

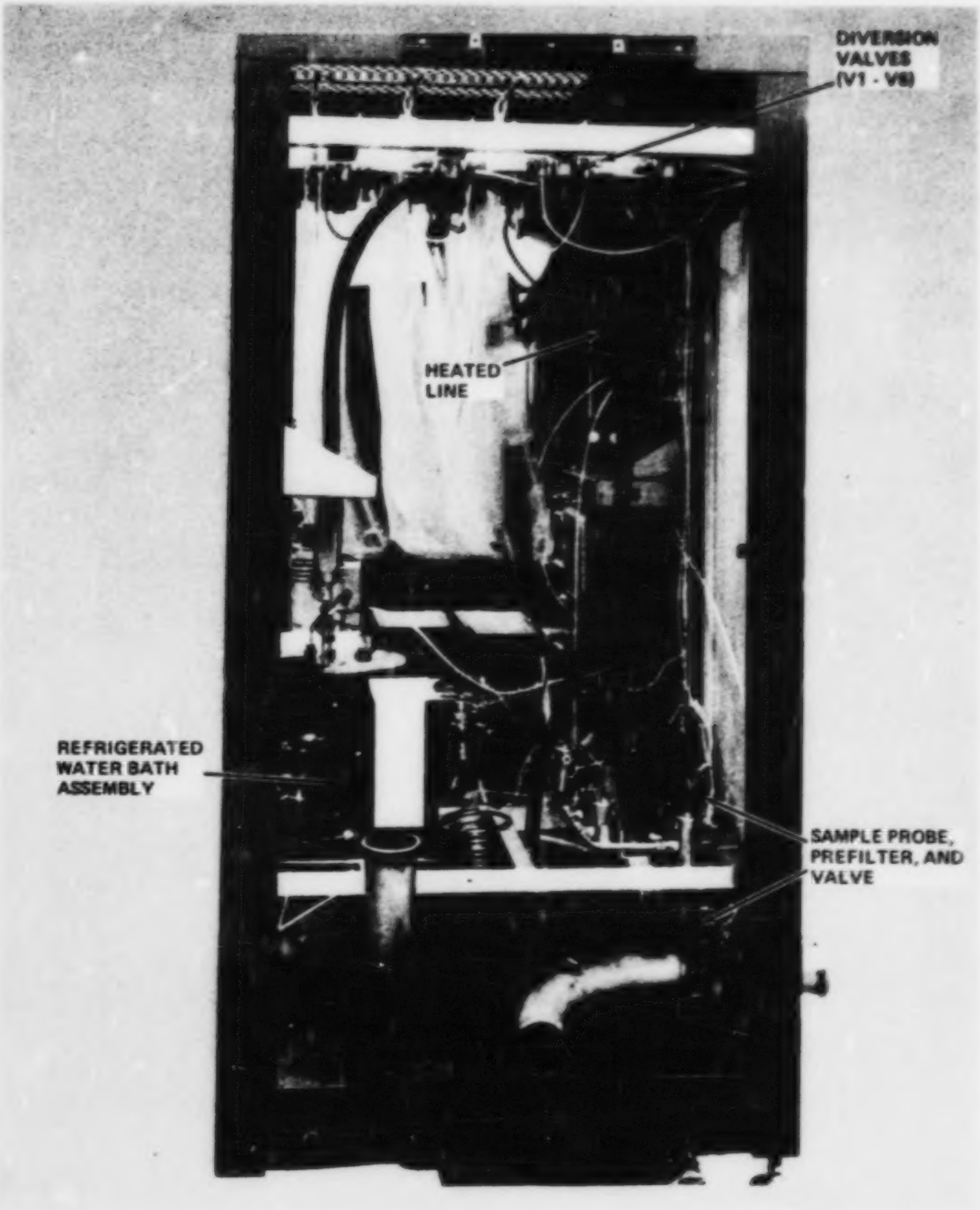

DIVERSION VALVES (V1 - V8)
HEATED LINE
REFRIGERATED WATER BATH ASSEMBLY
SAMPLE PROBE, PREFILTER, AND VALVE

Figure 7. Console interior (left side view, with heat exchanger removed)

At the center front bay of the console is the operator's control panel, flowmeter electronics, sample filter, heated line controller, and tailpipe backpressure gage. Console operations are reviewed in a subsequent paragraph.

The electronics assembly, including sequencing logic, signal processor, purge logic, pump logic, and valve, relay, and coil drivers, is housed in the right front bay of the console. The assembly consists of a vertical swing-out file with a hinged door (shown open in Figure 4). The individual components are mounted on 36 cards (6 rows by 6 columns) attached to the file frame. Most cards are connected to a +5 VDC and ground busses with integral noise suppression. The cards used for digital circuits feature integrated-circuit dual-in line-package (DIP) sockets. Individual digital components are simply plugged into these sockets. The sockets have pins extending through the card for wire-wrapping from the back side. This method of construction is uniquely suited for easy troubleshooting and repair of the electronics. The cards used for analog circuitry are specially fabricated from vector-board and feature primarily soldered connections within the card. Two cards are dedicated to input/output cables, one to the control panel and one to the sample valve, solenoid valves, relays, etc.

Visible in the interior views are the rear of the electronics assembly, power supplies, flowmeter, sample bags, pumps, water bath assembly, solenoid valves, heated line, sample valve coils, and transducers. In operation the console can be completely enclosed by the cabinet doors.

Operating Features

Operation of the proportional sampler involves the following typical pretest, test, and post-test steps.

Pretest - The operator first completes a purge cycle using the Purge Control selector switch. This sequence includes evacuation of residual sample from the bags, a flush of the sample probe, draining the sample condensate trap, filling the bags with purge air, and a final evacuation of the bags. The sample filter is changed and the heat exchanger tank is drained of exhaust condensate from the previous test.

The time intervals for the four phases of testing (in accordance with the 1975 CVS-CH procedure) are dialed in using the thumbwheel switches. Analog recorders may be set up to record any of five dynamic test parameters -- exhaust actual volume flow rate, exhaust standardized volume flow rate, gas temperature and pressure at the flowmeter, sample temperature at the sample valve inlet, and the sample open/close command signal.

The operator may select one of eight maximum expected exhaust flow rates, such that the sample valve pulse rate is maximized up to the 40 Hz limit. The operator checks the heated line and water bath temperatures and insures that the bag valve and flowmeter self-test switches are off.

Just before the test starts, the operator opens the exhaust cooling water valve to obtain the desired water flow rate, turns on power to the sample valve, and turns on the sample pump.

Test - The test sequence is initiated by momentarily closing the Start Test switch. Panel jacks are provided in parallel with this switch to enable setup of a remote start switch. The console then automatically sequences through the four test phases, including switchover of sample flow from bag to bag. The current test phase and elapsed time in that phase are continuously displayed on the control panel. The cumulative volume of exhaust (cubic feet at standard conditions) is continuously displayed for the three sample collection phases (e.g., cold transient, stabilized, and hot transient).

The operator monitors the various pressures and temperatures and estimates average values of sample line vacuum, water bath temperature, and exhaust temperature at the flowmeter. Values of ambient barometric pressure, temperature, and humidity are usually required.

Post-Test - After completion of the test sequence the sample pump sample valve power and cooling water are turned off. The essential test data are recorded for each phase, and the bag samples are transferred to an analysis system using the individually controlled bag drain valves (V4, V5, V6). Note that, if desired, each sample may be analyzed immediately after completion of its corresponding test phase without affecting subsequent samples.

EXHAUST FLOWMETER

The purpose of the exhaust flowmeter is to measure dynamically the vehicle exhaust volume flow rate. The flowmeter output signal is input to the signal processor as the basic parameter for controlling the sample flow rate.

The flowmeter selected for the proportional sampler is the vortex-shedding type. A summary of the theory of operation of this flowmeter is presented in the following paragraph, and is based upon the review provided in Reference 3.

The flow of fluid across a bluff (e.g., cylindrical) body will form a wake downstream of the body due to separation. For sufficiently high flow velocity, the wake will consist of a stable pattern of vortices, which have detached from alternate sides of the body and are moving downstream with the flow.

Numerous investigations have shown that over a wide range of flows, the following non-dimensional parameter, termed the Strouhal number, is practically constant:

$$S = fd/U \qquad (17)$$

where S = Strouhal number

f = vortex shedding frequency

d = body dimension normal to flow

U = fluid velocity

The principal deviation from constancy occurs at flow velocities just above initiation of the stable vortex pattern. However, the deviation is correlatable with the flow Reynolds number:

$$Re = \rho U d/\mu \qquad (18)$$

where Re = Reynolds number

ρ = fluid density

μ = fluid dynamic viscosity

In the flowmeter application the following relationship is employed:

$$Q \sim D^2 \, \overline{U} \sim D^2 \, df/S \, \{Re\} \qquad (19)$$

where Q = fluid volume flow rate

D = duct diameter

$\overline{U}$ = average fluid velocity in the duct

The repeatability of the phenomenon permits calibration of such a flowmeter over a wide range of operation. Development efforts have focused on optimum body shapes and reliable methods of vortex frequency detection.

The vortex frequency is detected, in the J-Tec unit, by passing an ultrasonic sound beam through the vortex trail. As the vortices intersect the sonic beam a modulation is imparted to the sonic signal, produced by a refraction-like effect when the sonic rays have their apparent velocities modified by the rotational velocity components of the vortices. Therefore, the received sonic signal contains an amplitude modulated component whose modulation frequency is the vortex-shedding frequency. The modulation amplitude imparted by the vortices varies as a function of the fluid velocity and the fluid density. However, since only the modulation frequency is of interest, these factors have no effect upon the measurement. The modulation frequency is detected and processed into a square wave whose frequency is again the vortex-shedding frequency and this is the principal output of the flowmeter. This can be utilized in a frequency to voltage converter to produce an analog output or can be directly counted in a digital counter for display purposes or for external usages.

Of importance in this type of flowmeter is the fact that the vortex frequency/volume flow scale factor is only a function of the vortex rod diameter. This implies that the system does not require periodic recalibration except in those cases where the vortex rod is eroded. Also, since the output is a frequency, amplifier drifts or offsets do not affect accuracy. The flowmeter electronics include bandpass filters to reject DC signal shifts and noise outside the vortex frequency range of interest.

An alternate flowmeter supplier, Eastech, Inc., was considered at the outset of the program. The Eastech design employed a thermistor as the vortex frequency detection method. The thermistor was mounted external to the main duct with connecting tubes to either side of the bluff body. The vortex trail would induce small flow perturbations in the tubing at the shedding fequency, and the thermistor signal could thus be converted into a pulse train. The two flowmeter designs were compared on the basis of metering accuracy, dynamic range, response, pressure loss, durability, cost, and development experience in the direct metering of automobile exhaust. The J-Tec design showed slight advantages in dynamic range, response, and pressure loss. However, the most significant factor was judged to be the development experience acquired with the J-Tec design (Reference 1). Although both designs appeared feasible, the Eastech model had not been tested with actual exhaust flow. Since the J-Tec model had been tested with apparent success in such an application, it was selected for use in the proportional sampler.

Detailed design of the flowmeter was performed by J-Tec, based upon the previous exhaust flowmetering application. The design parameters of significance include duct diameter, bluff body shape and cross-flow dimension, acoustic beam frequency, beam transmitter and receiver configuration, and duct length. The design criteria are:

(1) The strut Reynolds number ($\rho Ud/\mu$) must be greater than 50 for a stable vortex pattern to form.

(2) The duct Reynolds number ($\rho UD/\mu$) must be greater than 900 to prevent relaminarization.

(3) The maximum flow velocity measurable is limited by downstream drift of the acoustic beam, away from the receiver. For a given maximum volume flow this may require a larger duct diameter than that compatible with the above criteria. Alternatively, the meter's dynamic range may be compromised.

(4) The receiver electronics were limited to 10 kHz maximum shedding frequency.

(5) Efficient acoustic coupling is required between the transmitter/receiver transducers and the gaseous fluid medium.

(6) The beam transducers must be protected from the high temperature exhaust.

(7) The vortex scattering of the acoustic beam must have sufficient signal/noise ratio to avoid interference from fluid turbulence in the detection of the shedding frequency.

(8) The flow velocity profile across the duct should be essentially fully-developed.

Finally, the performance requirements for the flowmeter were originally specified as follows:

(1) Meter ambient air and internal combustion engine exhaust.

(2) Volume flow range from 17 to 510 m^3/hr.

(3) Static repeatability of 1/2 percent of reading.

(4) Resolution of 15,000 pulses per cubic meter (minimum).

(5) Time response equivalent to five pulse interval.

(6) Pressure loss less than 0.21 kPa at 510 m^3/hr.

(7) Gas temperature from 15°C to 260°C, with a goal of 425°C.

The resulting flowmeter configuration consists of a duct assembly and separate electronics chassis. The main duct is 137 cm long by 7.62 cm outside diameter. Fabricated from 0.165 cm thick stainless steel tubing, the internal flow diameter is 7.29 cm. The vortex-shedding strut is 114 cm downstream of the inlet flange, providing a flow development length of 15 diameters. A flow straightener consisting of 0.3175 cm cell size by 2.54 cm length stainless steel honeycomb is installed in the duct inlet to reduce flow turbulence.

The strut is a 0.239 cm diameter stainless steel rod mounted vertically across the duct. The ultrasonic beam is transmitted laterally across the duct approximately 0.5 cm downstream of the rod. The rod diameter, being slightly less than originally planned, provides a resolution of approximately 24,000 pulses per cubic meter of gas.

The beam transmitter and receiver transducers are piezoelectric crystals. The crystals are mounted in thermal-standoffs for protection from high temperature gas. Aluminum honeycomb was used inside each thermal standoff's cavity to collimate the beam. It was found necessary during development testing of the proportional sampler to replace the aluminum honeycomb with stainless steel honeycomb for improved durability.

The electronic chassis includes a power supply, transmitter signal driver, receiver signal conditioning, pulse and analog output signal drivers, and a self-test function which electronically simulates a flow of approximately 440 m^3/hr. The acoustic beam frequency was optimized at about 151 kHz. Relatively minor changes in the receiver signal conditioning were implemented during the development testing.

In light of the development test results, the use of thermal standoffs for the beam transducers was not required. This would permit future designs to be somewhat simpler and more reliable.

SAMPLE FLOW CONTROL VALVE

The sample flow control valve is an electromagnetically driven flapper valve operated in an open/close pulse mode. A schematic diagram of this type of valve is presented in Figure 8. The working end of the flapper opens and closes the inlet restrictor periodically drawing an exhaust gas sample. The valve critical flow orifice inlet meters the sample flow rate. The only moving part in the valve is the flapper-armature assembly, a cylindrical beam which is flexurally pivoted at its center. One end of the assembly serves as a common armature between two opposed electromagnets and the other end serves as a flapper between the restrictor and a fixed stop. The armature end is isolated from the valving end with a bellows mounted at the flexural pivot point. When an electrical command is given to one of the electromagnets, the resulting magnetic field draws the armature to the energized magnet. The flapper on the other end of the assembly is then forced to seat on the inlet restrictor blocking the inlet flow. Conversely, an electrical command to the opposite electromagnet reverses the armature motion. The flapper is forced away from the seat onto the fixed stop opening the valve. The valve may be operated at rates up to 40 samples per second with response times less than 4 milliseconds.

The internal construction of a valve similar to that used in the proportional sampler is illustrated in Figure 9. The actual sample valve design was derived from an existing hot gas (1200°C) valve used in a ballistic missile attitude control system. The valve body, flapper, flexure, and bellows are constructed of corrosion resistant stainless steel and nickel alloys. The armature and pole pieces are a Permendur 2V magnetic alloy. Each pair of pole pieces has a solenoid coil attached with a top bar to complete the magnetic circuit. Each coil is wound with 1000 turns and has 22 ohms resistance. A 38 VDC power supply is used to drive the coils, but in series with 5 ohm dropping resistors to limit the steady-state current to 1.4 amp per coil.

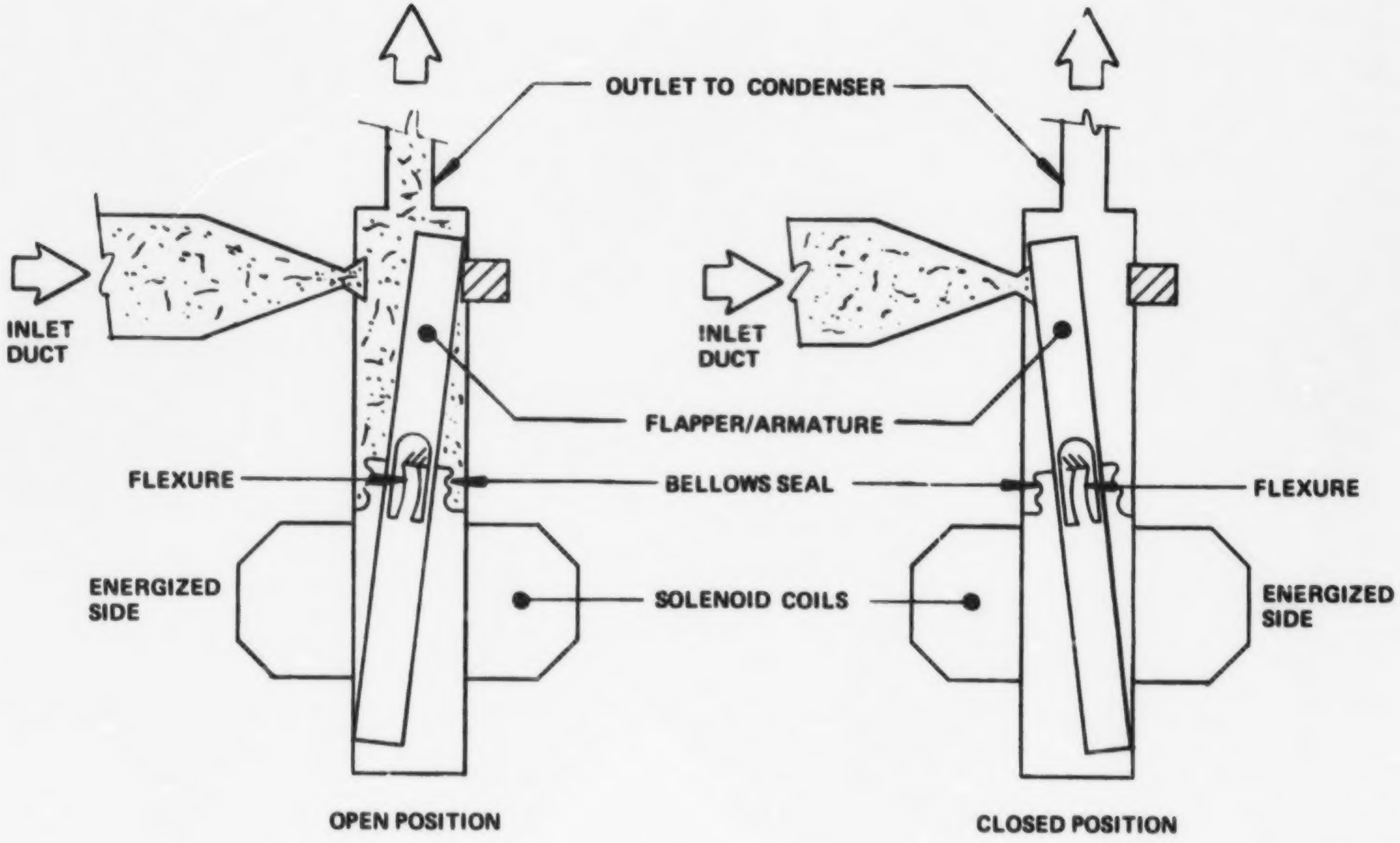

OUTLET TO CONDENSER
INLET DUCT
INLET DUCT
FLAPPER/ARMATURE
FLEXURE
BELLOWS SEAL
FLEXURE
ENERGIZED SIDE
SOLENOID COILS
ENERGIZED SIDE
OPEN POSITION
CLOSED POSITION

Figure 8. Sample flow control valve schematic diagram

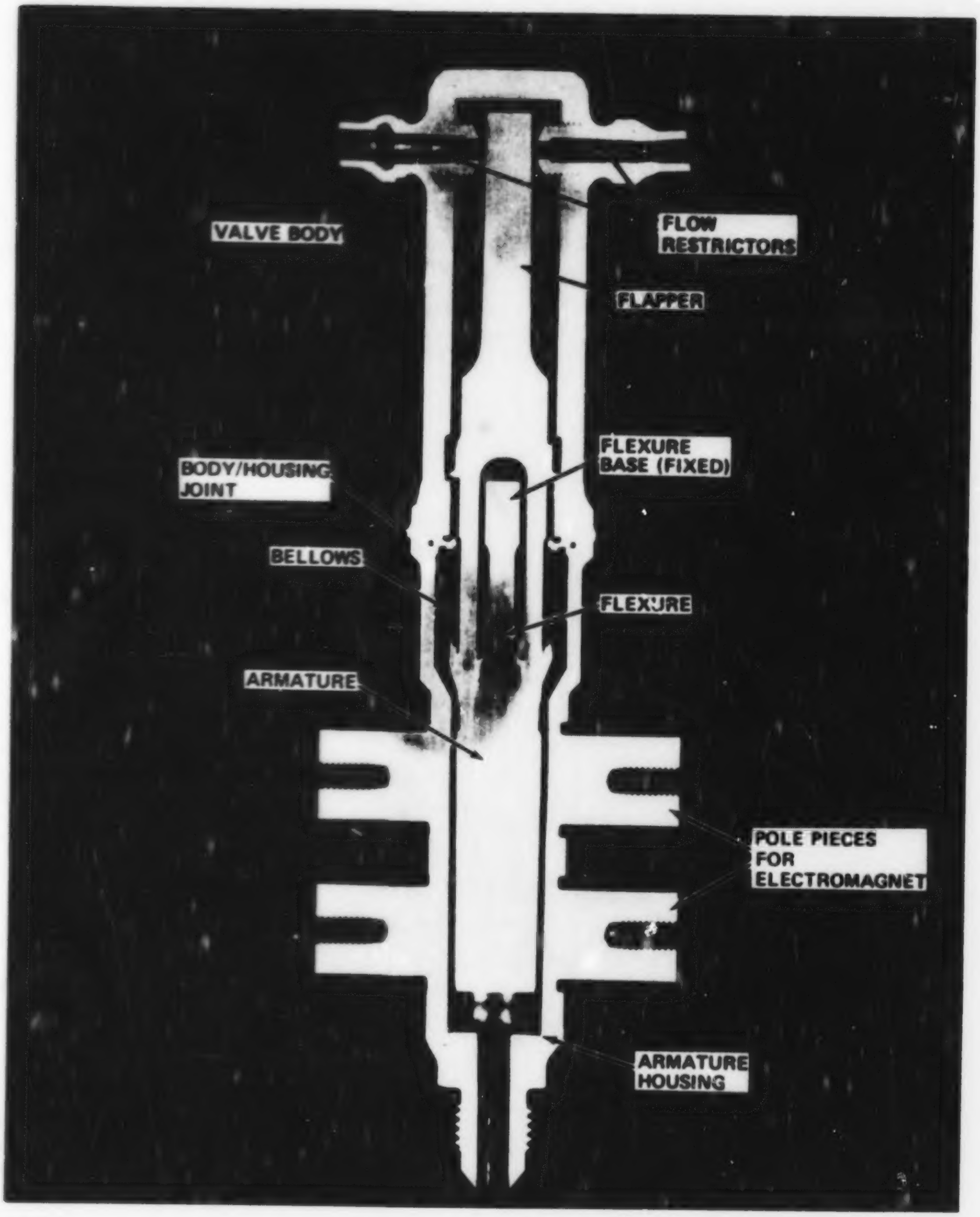

VALVE BODY
FLOW RESTRICTORS
FLAPPER
FLEXURE BASE (FIXED)
BODY/HOUSING JOINT
BELLOWS
FLEXURE
ARMATURE
POLE PIECES FOR ELECTROMAGNET
ARMATURE HOUSING

Figure 9. Flapper valve cross-section

The principal modifications of the existing valve design were in the restrictor/orifice configuration. These included:

(1) Reducing the flow area of the restrictor to obtain the desired full-open sample flow of about 16 lpm. An orifice diameter of 0.142 cm was used. To insure pulse-to-pulse repeatability the orifice throat was located upstream of the flapper seat.

(2) A 0.397 cm stainless steel ball was incorporated into the restrictor at the flapper end. This insures proper alignment of the sealing surface (spherical) against the restrictor outlet. The ball is trapped in a cavity at the restrictor outlet by the flapper.

(3) A threaded, rather than welded, jam nut is used to retain the restrictor in the valve body. A silicone O-ring is used to seal the nut against the body. This design permits disassembly of the restrictor and sealing ball for cleaning and/or replacement.

(4) The total flapper stroke was reduced from 0.102 cm down to 0.063 cm. This was permitted since only one restrictor is used, and the orifice flow area is reduced. The stroke reduction improves the valve response and flexure fatigue life.

(5) The second restrictor and an unrestricted part in the valve body were capped off since they are not required.

(6) The end cap on the valve body was replaced with a pipe thread adaptor (welded on) for use as the valve outlet. This change was made primarily to facilitate cleaning and reassembly of the valve.

SIGNAL PROCESSOR

The principal functions of the signal processing electronics are to (1) receive the flowmeter, pressure, and temperature signals, (2) provide open and close command signals to the sample flow control valve, (3) compute and display the cumulative standardized exhaust volume for each test phase, and (4) provide analog output signals of exhaust actual and standardized volume flow rates, flowmeter pressure and temperature, sample inlet temperature, and valve open/close commands. The selection of the design approach, processor equations, architecture, scale factors, and hardware implementation are reviewed in the following paragraphs.

Three approaches to the signal processor design were initially considered. These were: (1) analog computation, (2) general purpose microcomputer, and (3) special-purpose digital computation. An informal comparison of the three approaches was made on the issues of system accuracy, development effort, development risk, and equipment serviceability. Although the basic requirements were defined, the extent of nonlinearity compensation, computation speed capabilities, and reprogramming flexibility were uncertain factors in the evaluation. The results of the comparison are summarized in Table 2. The special purpose digital computer was the selected approach. The key factors were its inherent flexibility in tailoring of accuracy and speed characteristics, its minimum and predictable development effort, minimum risk, and its ease of service in the field.

Processor Equations

The processor functions may be described in terms of the computational tasks as follows:

(1) Linearize the temperature sensors' signals.

(2) Linearize the exhaust flowmeter signal.

(3) Determine the point in time at which the sample valve open command should be given.

(4) Determine the point in time at which the sample valve close command should be given.

(5) Accumulate and display the exhaust standardized volume.

(6) Determine the actual and standardized exhaust volume flow rates.

Temperature Sensor Linearization - The temperature sensors are identical platinum-wire probes whose resistance function follows the Callendar equation (Reference 4):

$$T = \frac{1}{\alpha}\left(\frac{R_+}{R_o} - 1\right) + \delta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right) \qquad (20)$$

where T = temperature (°C)

R_+ = resistance at temperature T (ohms)

R_o = resistance at 0°C (ohms)

α, δ = constants for platinum

Table 2. COMPARISON OF SIGNAL PROCESSOR DESIGN APPROACHES

Points of comparison	Analog computation	General purpose microcomputer	Special purpose digital computer
System accuracy	Marginal, due to amplifier drifts	Good, but could be speed-limited	Can be designed to meet resolution and speed requirements
Development effort	Equivalent to S/P digital, but less predictable	Highest, due to software development not compensated by hardware reductions	Equivalent to analog, but more predictable
Development risk	System complexity could increase to achieve required accuracy.	Best flexibility, but could require increase in programming effort to achieve satisfactory speed.	Minimum, due to use of read-only memories for non-linearity compensation.
Equipment serviceability	Marginal, due to extensive calibration requirements.	Good, but could require specialized programming support	Best, due to minimal calibrations.

The sensors are excited using fixed current sources and the resultant voltage amplified for input to the digital processor. Rather than use a complex computational algorithm to convert the nonlinear voltage signal into a temperature, the signal is linearized using what is essentially a table look-up method. The look-up table consists of a matrix of read-only memories (ROM's) programmed to provide a point-by-point description of the function. The voltage is input to an analog/digital (A/D) converter with a 10-bit unipolar binary output. This binary number is used as the address for the ROM matrix. The contents of each memory location is a 12-bit binary number representing the temperature at the sensor. The result is in the form of a normalized exhaust gas temperature and (using the same ROM matrix) a normalized sample valve inlet temperature:

$$\left.\begin{array}{l} T_1/T_s \\ \\ T_2/T_s \end{array}\right\} = \text{Function of temperature sensor voltage(s)} \qquad (21)$$

Flowmeter Linearization - At the low end of the flowmeter's dynamic range, a Reynolds number effect becomes significant and the actual volume flow is not quite proportional to the vortex shedding frequency. The Reynolds number will vary primarily with vortex frequency, secondarily with gas temperature (through both density and viscosity), and only slightly with gas pressure. It is convenient to measure the vortex frequency by measuring the elapsed time between flowmeter pulses:

$$\Delta t_m = \frac{1}{f} = \text{flowmeter pulse interval (sec)} \qquad (22)$$

Without the Reynolds number effect the exhaust volume for flowmeter pulse would be constant:

$$\Delta Q_A = \frac{Q_A \, \Delta t_m}{3600} \sim f \, \Delta t_m = \text{constant} \qquad (23)$$

where ΔQ_A = exhaust volume per pulse (m^3)

This suggests the use of the flowmeter pulse to trigger a computational sequence involving the exhaust volume increment, the corresponding sample volume increment, and a standardized volume increment. This leads to a relatively simple, but general, method for linearizing the flowmeter output. The Reynolds number becomes:

$$Re = \frac{\rho U d}{\mu} \sim \frac{1}{\Delta t_m \, (T_1)^{1+\nu}} \qquad (24)$$

where the approximate gas viscosity temperature relation has been used:

$$\mu \sim (T)^{\nu} \tag{25}$$

and where ν = gas viscosity temperature exponent

Since the gas pressure does not vary widely its dynamic effect on Reynold's number is neglected. From Equation 24 it can be noted that a single variable will describe the variation in Reynolds number with vortex frequency and gas temperature. This suggests the use of a ROM matrix in the same manner as the temperature sensor linearization. Using a normalized temperature the form of the equation is:

$$\Delta Q_A = \text{Function of } \Delta t_m \, (T_1/T_s)^{1+\nu} \tag{26}$$

The independent variable in this function must first be computed from the input parameters. This can be done in two steps. First a ROM matrix is used to evaluate the temperature power function:

$$[(T_1/T_s)^{1+\nu}] = \text{Function of } (T_1/T_s) \tag{27}$$

Then this ROM output is multiplied by the measured value of the flowmeter pulse interval:

$$\left[\Delta t_m \, (T_1/T_s)^{1+\nu}\right] = (\Delta t_m) \times \left[(T_1/T_s)^{1+\nu}\right] \tag{28}$$

Sample valve open/close commands - With the exception of the three ROM matrices described above, the remaining processor operations are simple additions, subtractions, multiplications, and divisions. The problem of controlling the sample valve is formulated in terms of accumulating the increments of desired sample flow for each flowmeter pulse until they are equal to the sample flow admitted in a single valve open/closed cycle. For convenience a fixed valve open time is used. Thus a clock is started when the valve is opened, and the valve is closed when the clock reaches the (selectable) value for t_o. The steps involved are:

(1) Temperature compensation of exhaust volume --

$$\left[\Delta Q_s \, (P_s/P_1)\right] = (\Delta Q_A) : (T_1/T_s) \tag{29}$$

(2) Application of the (selectable) proportionality constant --

$$\left[\frac{\Delta Q_s \, (P_s/P_1)}{q_m/k}\right] = \left[\Delta Q_s \, (P_s/P_1)\right] : (q_m/k) \tag{30}$$

(3) Square-root of sample inlet temperature (using successive approximation divisions) --

$$(T_2/T_s)^{1/2} = (T_2/T_s) \div (T_2/T_s)^{1/2} \qquad (31)$$

(4) Standardized sample volume per flowmeter pulse --

$$\Delta q_s = \left[\frac{\Delta Q_s \; (P_s/P_1)}{q_m/k} \right] \times (T_2/T_s)^{1/2} \qquad (32)$$

(5) Sample leakage factor per flowmeter pulse --

$$(\lambda_1 \; \Delta t_m) = (\lambda_1) \times (\Delta t_m) \qquad (33)$$

(6) Summation of sample standardized volume increments over the valve cycle --

$$\begin{aligned} &\sum_{\text{cycle}} [(\Delta q_s) - (\lambda_1 \; \Delta t_m)] \\ &= \sum_{\text{cycle-1}} [(\Delta q_s) - (\lambda_1 \; \Delta t_m)] + (\Delta q_s) - (\lambda_1 \; \Delta t_m) \end{aligned} \qquad (34)$$

(7) Valve open command criterion --

$$\sum_{\text{cycle}} [(\Delta q_s) - (\lambda_1 \; \Delta t_m)] \geq [t_o \; (\lambda_o - \lambda_1)] \qquad (35)$$

(8) Reset cumulative standardized sample volume (after valve-open command) --

$$\begin{aligned} &\sum_{\text{INITIAL}} [(\Delta q_s) - (\lambda_1 \; \Delta t_m)] \\ &= \sum_{\text{CYCLE}} [(\Delta q_s) - (\lambda_1 \; \Delta t_m)] - [t_o \; (\lambda_o - \lambda_1)] \end{aligned} \qquad (36)$$

where ΔQ_s = standardized exhaust volume per pulse (m^3)

Δq_s = standardized sample volume per flowmeter pulse (seconds, due to normalization by q_m)

and where the quantity t_o ($\lambda_o - \lambda_1$) is a lumped input to the processor.

Cumulative exhaust standardized volume - The cumulative volume is obtained in two steps:

(1) Pressure compensation of exhaust volume --

$$\Delta Q_s = [\Delta Q_s (P_s/P_1)] \times (P_1/P_s) \qquad (37)$$

(2) Summation of standardized exhaust volume increments over the test phase --

$$V = \sum_{\text{TEST}} (\Delta Q_s) \qquad (38)$$

Exhaust volume flow rates - Since these are not used directly in the processor, they must be calculated for digital to analog (D/A) conversion and output to the operator's panel. The equations are simply:

(1) Actual volume flow rate --

$$Q_A = (\Delta Q_A) \div (\Delta t_m) \qquad (39)$$

(2) Standardized volume flow rate --

$$Q_s = (\Delta Q_s) \div (\Delta t_m) \qquad (40)$$

Processor Architecture

A simplified block diagram of the signal processor is provided in Figure 10. The heart of the processor is a 12-bit by 12-bit multiplier which is sequenced through the equations step by step. Division is performed using the multiplier in a successive approximation mode. The other principal components are the three ROM matrices, input switches for digital constants, registers for intermediate parameters, and accumulators for addition and subtraction.

The multiplier sequence of operations is summarized in Table 3. The full sequence of computations is performed (within approximately 100 μs) for each flowmeter pulse, and is initiated by the pulse. Evaluation of Equations 21 and 27 is essentially immediate. Then Equation 28 is evaluated in the first step of the multiplier sequence, and also results in immediate evaluation of Equation 26. Equations 29 through 33 are then evaluated in multiplier steps 2 through 6 respectively. Equations 34, 35 and 36 are evaluated independent of the multiplier in the valve on/off control. Meanwhile Equation 37 is evaluated in multiplier step 7 with Equation 38 evaluated subsequently in the exhaust volume accumulator. The volume display is incremented from the accumulator each second of the test period. Meanwhile the multiplier sequence is completed with the valuation of Equations 39 and 40 in steps 8 and 9 respectively. After each sequence the analog signal inputs are updated for the next sequence.

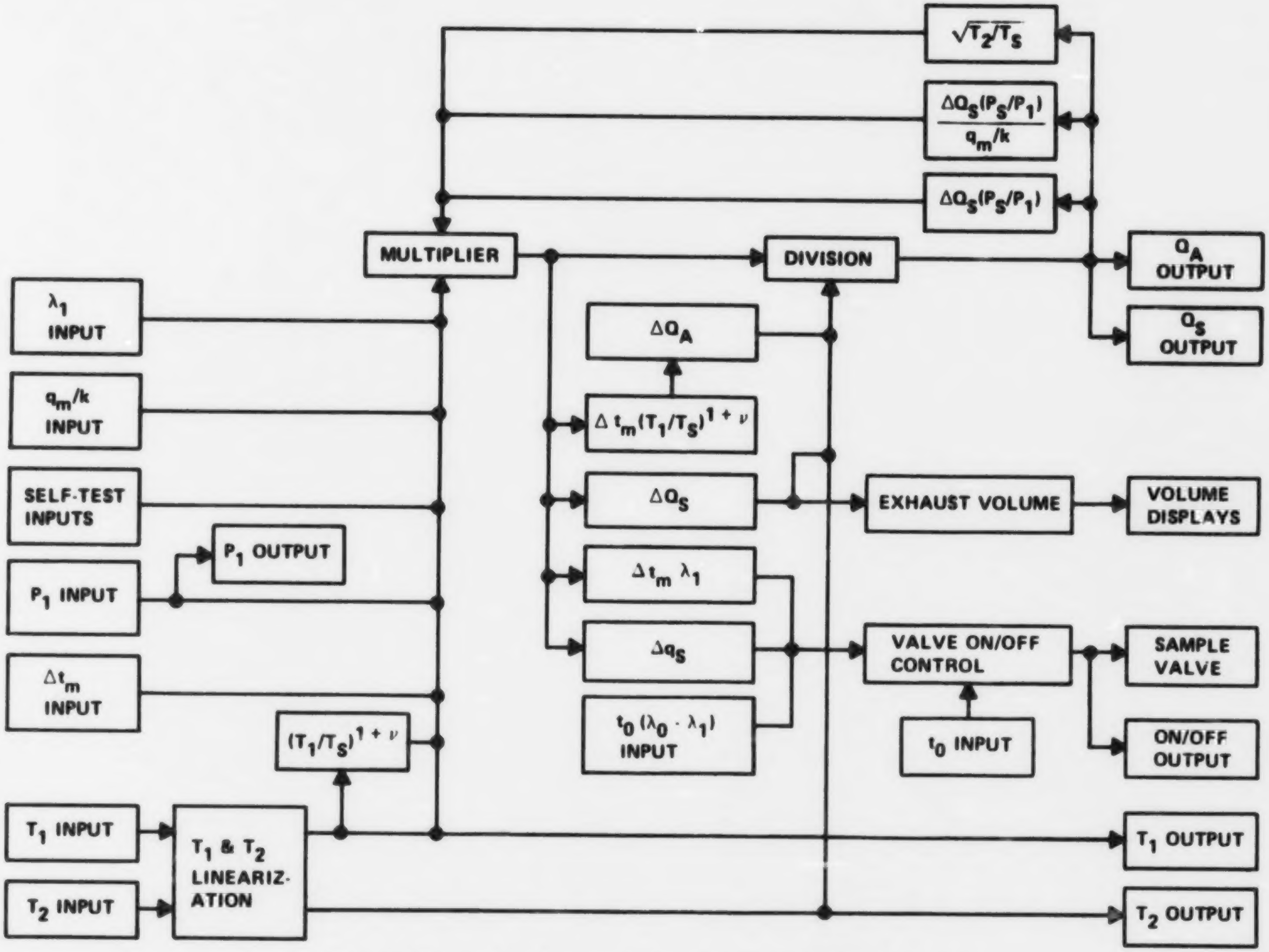

$\sqrt{T_2/T_S}$
$\frac{\Delta Q_S(P_S/P_1)}{q_m/k}$
$\Delta Q_S(P_S/P_1)$
MULTIPLIER
DIVISION
Q_A OUTPUT
Q_S OUTPUT
λ_1 INPUT
q_m/k INPUT
SELF-TEST INPUTS
P_1 OUTPUT
P_1 INPUT
Δt_m INPUT
$(T_1/T_S)^{1+\nu}$
T_1 INPUT
T_2 INPUT
T_1 & T_2 LINEARIZ-ATION
ΔQ_A
$\Delta t_m(T_1/T_S)^{1+\nu}$
ΔQ_S
$\Delta t_m\ \lambda_1$
Δq_S
$t_0\ (\lambda_0 \cdot \lambda_1)$ INPUT
EXHAUST VOLUME
VOLUME DISPLAYS
VALVE ON/OFF CONTROL
t_0 INPUT
SAMPLE VALVE
ON/OFF OUTPUT
T_1 OUTPUT
T_2 OUTPUT

Figure 10. Signal processor simplified block diagram

Table 3. MULTIPLIER SEQUENCE OF OPERATIONS

Step	Equation reference	Operation	Multiplicand (denominator)	Multiplier (quotient)	Product (mumerator)
1	(28)	Multiply	Δt_m	$(T_1/T_s)^{1+\nu}$	$[\Delta t_m \ (T_1/T_s)^{1+\nu}]$ $\rightarrow \Delta Q_A$
2	(29)	Division	(T_1/T_s)	$[\Delta Q_s \ (P_s/P_1)]$	ΔQ_A
3	(30)	Division	$[q_m/k]$	$\left[\frac{\Delta Q_s \ (P_s/P_1)}{q_m/k}\right]$	$[\Delta Q_s \ (P_s/P_1)]$
4	(31)	Division (square root)	$(T_2/T_s)^{1/2}$	$(T_2/T_s)^{1/2}$	(T_2/T_s)
5	(32)	Multiply	$(T_2/T_s)^{1/2}$	$\left[\frac{\Delta Q_s \ (P_s/P_1)}{q_m/k}\right]$	Δq_s
6	(33)	Multiply	Δt_m	λ_1	$(\lambda_1 \ \Delta t_m)$
7	(37)	Multiply	(P_1/P_s)	$[\Delta Q_s \ (P_s/P_1)]$	ΔQ_s
8	(39)	Divide	Δt_m	Q_A	ΔQ_A
9	(40)	Divide	Δt_m	Q_s	ΔQ_s

The binary arithmetic scaling factors (into engineering units) for the processor parameters are provided in Table 4. These factors were derived in conjunction with an overall system accuracy analysis. The analysis considered potential errors arising from the following sources:

(1) Flowmeter and sensor installations (false reading of true parameter).

(2) Calibrations (reference reading not equal to true parameter).

(3) Uncompensated nonlinearity.

(4) Transducer and analog signal conditioning nonrepeatability.

(5) Digital signal processing errors (resolution or truncation effect in the operations of A/D conversion, ROM function generation, multiplication and division, and D/A conversion).

The last of these error sources is primarily controlled by proper selection of the digital word length (e.g., 12 bits or 1 part in 2^{12} resolution).

Truncation errors can be assumed to accumulate in a root-sum-square fashion for independent operations (Reference 5). The individual truncation error will decrease as the inverse of 2^n where n is the number of bits per word. Thus a 12-bit word has one-quarter of the truncation error of a 10-bit word, and one-sixteenth that of an 8-bit data word. It was found desirable to use a 12-bit word length for the processor, except for the ROM address words wherein the size of the ROM matrix doubles for each additional address bit. Also the A/D and D/A conversions could be performed with sufficient accuracy using 10-bit word lengths.

Electronic Implementations

The following paragraphs provide summary descriptions of the electronics involved in the signal processor.

Flowmeter Input - The flowmeter pulse train is timed using a high-speed (3/8 microsecond interval) clock input to a 16-bit counter. Receipt of a flowmeter pulse gates the counter total into a storage register, resets the counter to zero, and enables the counter to accumulate clock pulses for the next flowmeter pulse.

Analog Inputs - The pressure and temperature signals are derived from passive transducers. Excitation is provided from a +6.35 VDC reference voltage obtained from the ±15 supply using a stable zener diode. The

Table 4. SIGNAL PROCESSOR PARAMETER BINARY SCALING FACTORS

Parameter (engineering units)	Location in processor	Resolution MS - Most significant LS - Least significant	Least significant bit (LSB) value	Full-scale value
Δt_m (seconds)	Input register	16 bits	0.375 E-6	24.57 E-3
	Multipliers 1 & 6	MS 12 bits	6.0 E-6	24.57 E-3
	Denominators 8 & 9	LS 12 bits	0.375 E-6	1.535 E-3
(T_1/T_s) & (T_2/T_s)	Linearization output	12 bits	0.6 E-3	2.457
	$(T_1/T_s)^{1+\nu}$ input	MS 10 bits	2.4 E-3	2.455
T_s = 293.15°K	Denominator 2	12 bits	0.6 E-3	2.457
	Numerator 4	24 bits	0.1465 E-6	2.457
	D/A inputs	MS 10 bits	2.4 E-3	2.455
(P_1/P_s)	A/D output	MS 10 bits	1.04 E-3	1.064
P_s = 101.325 kPa	Multiplier 7	12 bits	0.26 E-3	1.065
$(T_1/T_s)^{1+\nu}$	ROM output Multiplier 1	12 bits	1.2 E-3	4.914
$[\Delta t_m\ (T_1/T_s)^{1+\nu}]$ (seconds)	Product 1	24 bits	7.2 E-9	0.1208
	ΔQ_A ROM Input	MS 10 bits	0.118 E-3	0.1207
ΔQ_A (m^3)	ROM output	12 bits	0.0997 E-6	0.4083 E-3
	Numerators 2 & 8	24 bits	0.0243 E-9	0.4083 E-3

Table 4 (continued). SIGNAL PROCESSOR PARAMETER BINARY SCALING FACTORS

Parameter (Engineering units)	Location in processor	Resolution MS - Most significant LS - Least significant	Least significant bit (LSB) value	Full-scale value
$\Delta Q_s \ (P_s/P_1) \ (m^3)$	Quotient 2 Multiplier 7 Numerator 3	12 bits 12 bits 24 bits (2 bit shift left)	0.0406 E-6 0.0406 E-6 0.0396 E-9	0.1662 E-3 0.1662 E-3 0.6649 E-3
$[q_m/k] \ (m^3/sec)$	DIP switch input Denominator 3	MS 8 bits 12 bits	1.987 E-3 0.1242 E-3	0.5066 0.5086
$\left[\frac{\Delta Q_s \ (P_s/P_1)}{q_m/k}\right]$ (seconds)	Quotient 3 Multiplier 5	12 bits	0.319 E-6	1.306 E-3
$(T_2/T_s)^{1/2}$	Quotient 4 Multiplier 5	12 bits	0.3827 E-3	1.567
Δq_s (seconds)	Product 5 Summation register	24 bits MS 12 bits	0.1221 E-9 0.5 E-6	2.048 E-3 2.048 E-3
λ_1	DIP switch input Multiplier 6	MS 8 bits 12 bits	0.3255 E-3 20.35 E-6	0.0830 0.0833
$\lambda_1 \ \Delta t_m$ (seconds)	Product 6 Summation register	24 bits MS 12 bits	0.1221 E-9 0.5 E-6	2.048 E-3 2.048 E-3
$t_o \ (\lambda_o - \lambda_1)$ (seconds)	DIP switch input Summation register	MS 8 bits 16 bits	0.128 E-3 0.5 E-6	0.03264 0.03276

Table 4 (continued). SIGNAL PROCESSOR PARAMETER BINARY SCALING FACTORS

Parameter (engineering units)	Location in processor	Resolution MS - Most significant LS - Least significant	Least significant bit (LSB) value	Full-scale value
t_o (seconds)	DIP switch input	MS 8 bits	0.096 E-3	0.02448
	Valve-on timer	16 bits	0.375 E-6	0.02457
ΔQ_s (m^3)	Product 7	24 bits	0.01055 E-9	0.1770 E-3
	Summation register	MS 12 bits	0.04321 E-6	0.1770 E-3
	Numerator 9	24 bits (1 bit shift left)	0.0211 E-9	0.3540 E-3
V (m^3)	Summation register	30 bits	0.04321 E-6	46.38
	Binary/decimal comparator	MS 14 bits	2.832 E-3	46.38
	Decimal displays	4 decimals	2.832 E-3 (0.1 cubic feet)	28.31 (999.9 cubic feet)
Q_A (m^3/hr)	Quotient 8	12 bits	0.2338	957.1
	D/A input	MS 10 bits	0.9351	956.7
Q_s (m^3/hr)	Quotient 9	12 bits	0.2025	829.3
	D/A input	MS 10 bits	0.8101	828.8

signals are amplified up to 0-10 VDC range and input to the A/D converters. Each signal has a dedicated 10-bit A/D converter.

Read-only Memory Functions - The three ROM functions employ identical matrices of memory chips. Each chip is organized into 256 words, by 4-bit word length. The 12-bit output is obtained by combining three chips -- least-significant, intermediate-significant, most-significant bits (LSB, ISB, MSB) -- into a column. Since the input resolution is 10 bits, each ROM matrix has four columns, with each column using the most-significant 8 bits of the input. The least significant 2 bits determine which column is selected. Since the memory chips are tri-state output devices, the column outputs are wired in common. Only the selected column is active.

Multiplier - The multiplier forms a 24-bit product from two 12-bit inputs. The product is formed from eighteen 4-bit sub-products obtained in parallel multiplications using 4-bit by 4-bit multiplier chips. The parallel multiplication requires less than 1 microsecond for completion. Typically only the most significant 12 bits of the 24-bit product are carried forward in the computation. Each input to the multiplier is gated through an 8-into-1 digital multiplexer. A single multiplexer chip is used for each of the 12 input bits. The specific input to be used in each step of the multiplier sequence is controlled by the processor timing through selection of the multiplexers' input channel.

Division - Division, including a square-root operation, is performed as a series of multiplications. A successive approximation register (SAR) is used as a quotient generator. The SAR begins a division with the MSB = 1 and all other bits = 0. Then a multiplication is performed between the SAR output and the denominator input to yield an estimate of the numerator as the product. This estimate is compared with the actual numerator input and the SAR MSB is reset to zero if the estimate is greater than the actual numerator. This routine is repeated for each bit of the SAR in descending significance. The five numerators in the computational sequence are gated into the product/numerator comparator through a multiplexer in accordance with processor timing. Note that for the square root operation the SAR is input to both inputs of the multiplier. The final SAR quotient is gated to the appropriate storage register by the processor timing.

Sample Valve On/Off Control - For each flowmeter pulse the incremental sample mass is added to a storage register, the valve leakage increment is subtracted from this register, and the cumulative result is compared to the selected cycle scaling input switch t_o $(\lambda_o - \lambda_1)$. When the register sum exceeds the switch value the sample valve is commanded open. Simultaneously a valve-open timer is started. This timer consists of a counter with a clock pulse input (3/8 microsecond interval). When the counter value matches the value set into the valve-open time switch, the valve is commanded closed. Meanwhile after the valve-open command the cycle scaling parameter value is subtracted from the storage register to reset this sum for the next valve cycle. The valve-open and -close commands are output to jacks on the operator's control panel as well as to the sample valve coil drivers.

Exhaust Mass Accumulator - For each flowmeter pulse the incremental exhaust standardized volume is added to a storage register. The register, reset only at the beginning of a test phase interval, maintains a running total. However, this total is in the binary form in this register. This binary number must be converted to a decimal number for display on the control panel. This conversion is done by gating a clock pulse train simultaneously into a binary counter and into a decimal counter. The value in the binary counter is compared with the value of the cumulative exhaust mass register. When the two binary numbers agree, the clock pulses are stopped, and the value in the decimal counter is sent to the display drivers.

Exhaust Volume Displays - The three exhaust standard volume displays on the control panel consist of four decimal digit display modules. Each module is a seven-segment incandescent lamp which operates off of the +5 VDC power supply. Each digit is driven by a standard seven-segment driver chip which decodes the binary-coded decimal (BCD) input from the decimal counter. Each 4 digit display includes an input multiplexer and storage register as part of the signal processor self-test capability. The volume displays are updated each second of the test interval.

Analog Outputs - With the exception of exhaust gas pressure, the analog output signals are obtained from the processor through 10-bit D/A converters. The output voltage range is 0 to 10 VDC. Since the pressure transducer features excellent linearity this signal is not corrected within the digital signal processor. Thus the analog output is derived directly from the analog input.

Self-Test Aids - A substantial self-test capability has been built into the signal processor to aid users in troubleshooting the electronics. The self-test features include: (1) switchover of input parameters to dual in-line package (DIP) switches which are under manual control, (2) static display of nearly all internal parameters via the control panel volume displays, and (3) dynamic display of key parameters during a test on the volume displays. Individual bits may thus be checked in any of the processor modules. These features are in addition to a static system test capability implemented through the exhaust flowmeter.

EXHAUST HEAT EXCHANGER

When it was determined that the flowmeter would not perform accurately for high temperature (>65°C) flows, the incorporation of an exhaust heat exchanger into the proportional sampler was selected as the most expeditious resolution of the problem. A flowmeter gas temperature of 40°C or less was specified as the principal heat exchanger performance requirement. The exhaust cooling load was estimated as a function of exhaust inlet temperature, outlet temperature, and flow rate. The results are presented in Figure 11. For outlet temperatures below about 50°C the heat rejection associated with the condensation of water vapor becomes significant. The assumption is made that the exhaust is saturated at the outlet temperature.

An open-cycle (i.e., no return of coolant) water-to-exhaust heat exchanger concept was selected as the basic design approach. The theoretical cooling capacity of such an exchanger is presented in Figure 12 as a function of water flow rate and temperature rise. Figures 11 and 12 indicate that a water flow of 20 to 40 lpm would provide adequate cooling power for the exhaust flows and temperatures expected. The design constraints for a practical exchanger configuration were as follows:

(1) The nominal facility water supply pressure is 345 kPa. No auxiliary water pump should be used.

(2) The total exhaust pressure loss through the proportional sampler, including the heat exchanger, should not exceed 1.25 kPa at 400 m^3/hr. The allowable loss due to the heat exchanger was estimated at 0.5 kPa.

(3) The exchanger should be designed for packaging within the (pre-existing) exhaust plenum tank (40.6 cm diameter by 182.8 cm height). This constraint was considered most practical in view of the allowable exhaust pressure loss and the desire to avoid water vapor condensation prior to sampling of the exhaust. A secondary benefit was the possibility of further attenuating acoustic noise within the plenum tank.

Within these constraints the most promising configuration appeared to be a vertical column of coiled tubing through which the cooling water would pass. The exhaust would be forced to pass back and forth four times across the tubing by the use of baffles within the tank, as diagrammed in Figure 13. The water inlet and outlet connections would pass through bulkhead fittings at the front of the tank. Although a counter-flow arrangement appeared most efficient, a parallel-flow design could be obtained by simply switching the external water connections.

Stainless steel was selected for the tubing on the basis of its durability in the exhaust and cooling water environments. A standard tubing size of 1.905 cm outside diameter by 0.124 cm wall thickness was selected on the basis of an acceptable water pressure drop at a flow of 20 lpm. The tubing was available in lengths of about 6 m, necessitating the use of twelve coil segments to achieve a total tubing length of approximately 70 m. The segments were joined using 90 degree elbow, flareless tube fittings. The coil diameter was selected as the maximum compatible with assembly inside the plenum tank. The inner and outer baffles were cut from stainless steel sheet stock. The spacing between each coil of tubing was specified to provide for a maximum exhaust-side heat transfer

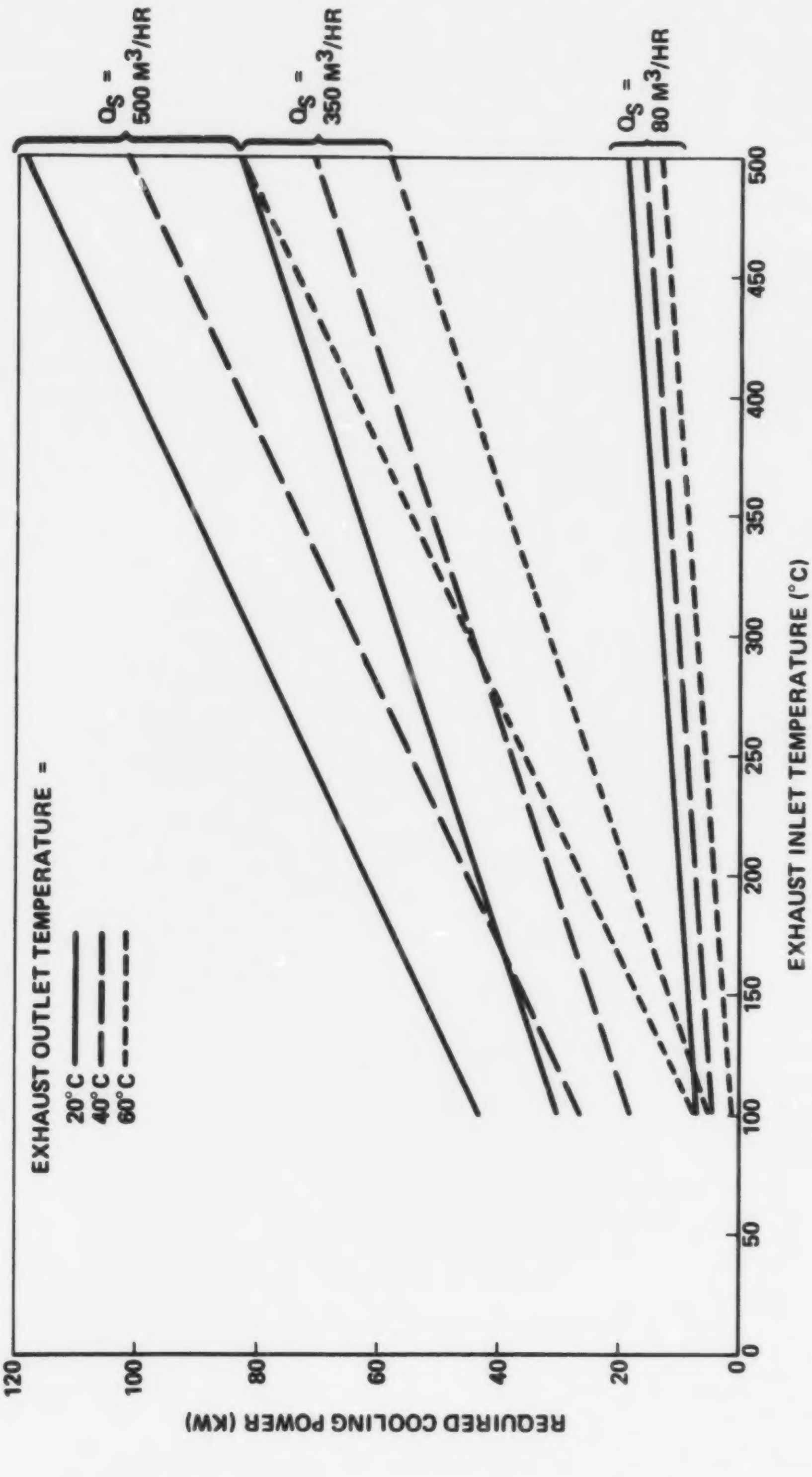


Figure 11. Exhaust cooling load estimates

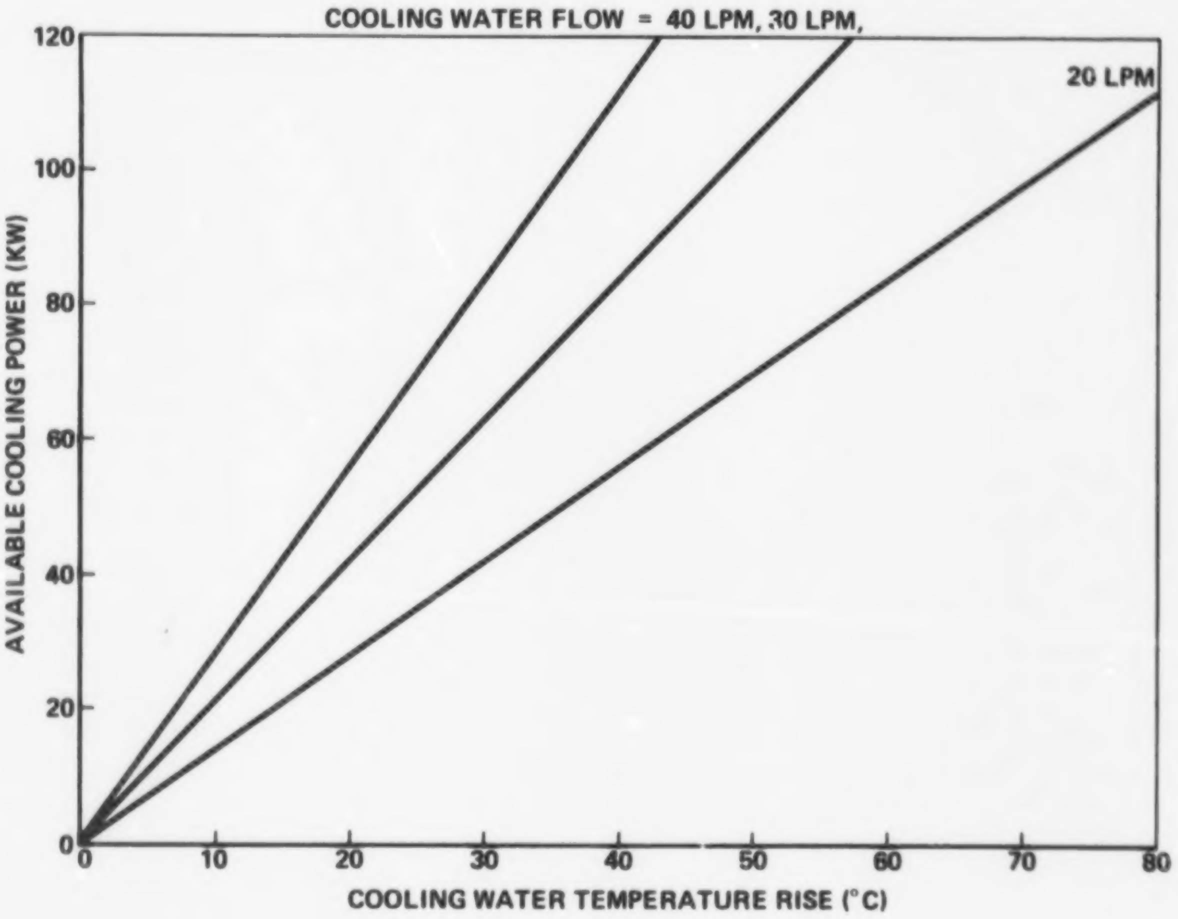


Figure 12. Cooling capacity for open-cycle water-exhaust head exchanger

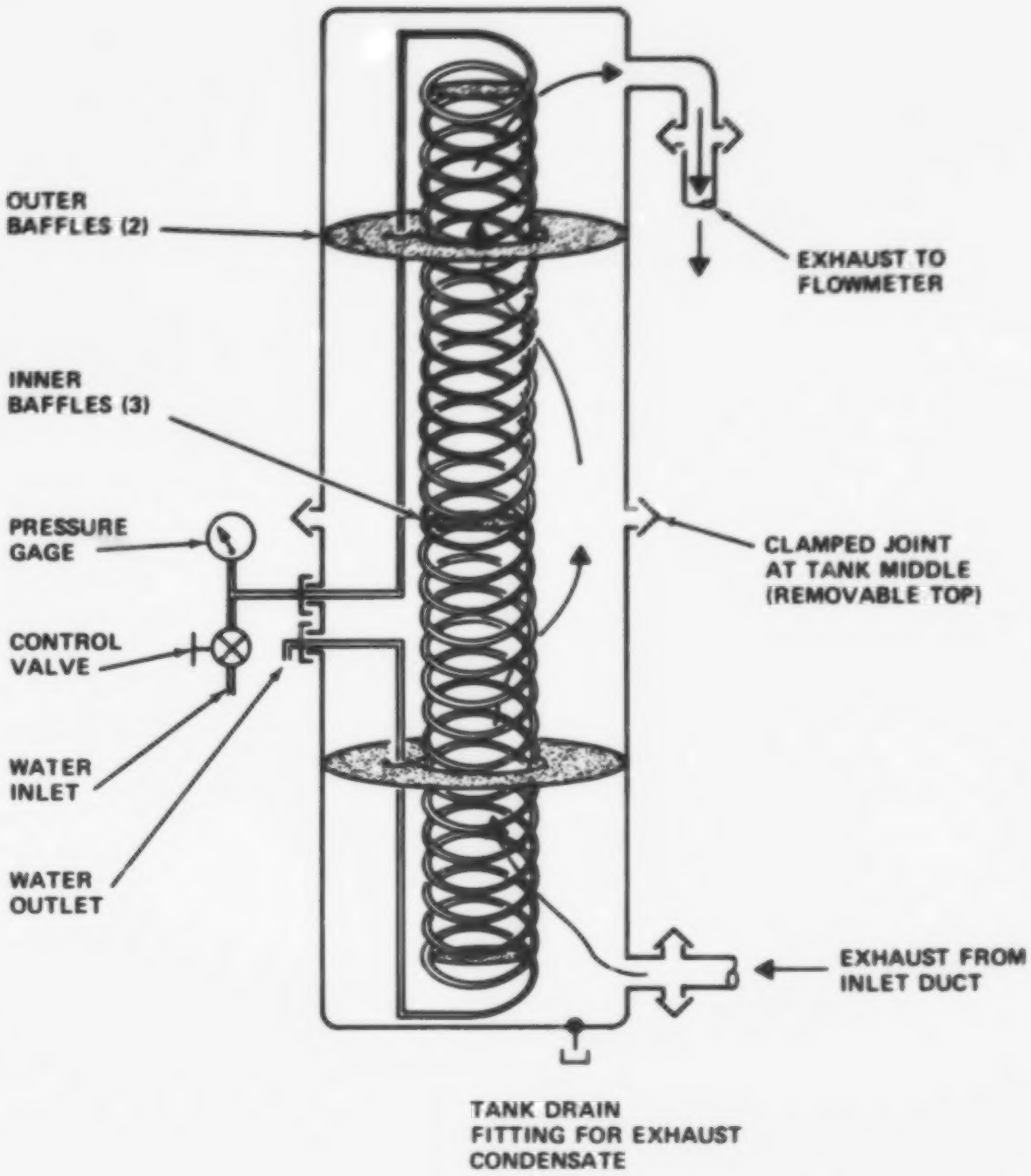

OUTER BAFFLES (2)
EXHAUST TO FLOWMETER
INNER BAFFLES (3)
PRESSURE GAGE
CLAMPED JOINT AT TANK MIDDLE (REMOVABLE TOP)
CONTROL VALVE
WATER INLET
WATER OUTLET
EXHAUST FROM INLET DUCT
TANK DRAIN FITTING FOR EXHAUST CONDENSATE

Figure 13. Exhaust heat exchanger schematic diagram

coefficient consistent with the allowable pressure loss of 0.125 kPa per stage. This spacing, nominally 0.0635 cm, was controlled by weaving stainless steel wire around each coil.

The final cooling coil assembly is illustrated in Figure 14 just prior to installation of the top half of the tank over the assembly. Note the 0.635 cm tubing frame around the coil at the top and middle of the assembly. Together with a third such frame at the tank bottom, these and the two outer baffles provide five-point lateral support for the coil within the tank. The heat exchanger and plenum tank together weigh approximately 85 kgm, including 15 kgm of water in the coil assembly.

The methods of Reference 6 were used to estimate the performance of the final heat exchanger design. The results are presented in Figure 15, which illustrate the generally satisfactory level of exhaust temperature reduction. The resistance to heat transfer from the exhaust-to-tubing outer surface constitutes 98 percent of the overall resistance to heat transfer from the exhaust to the cooling water. This, along with the cooling load, accounts for the variation in exhaust outlet temperature with flow rate. The actual variation in exhaust outlet temperature is relatively small due to the large thermal inertia of the exchanger assembly. Thus the actual outlet temperature corresponds principally to the average exhaust flow rate over about one minute.

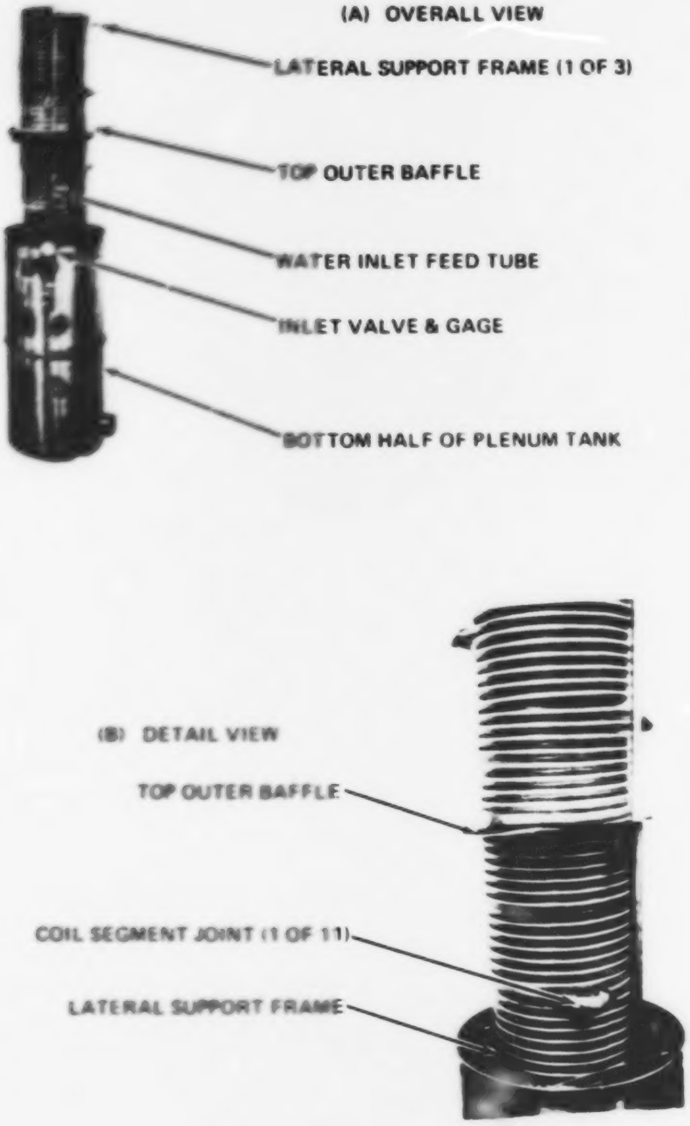

(A) OVERALL VIEW
LATERAL SUPPORT FRAME (1 OF 3)
TOP OUTER BAFFLE
WATER INLET FEED TUBE
INLET VALVE & GAGE
BOTTOM HALF OF PLENUM TANK
(B) DETAIL VIEW
TOP OUTER BAFFLE
COIL SEGMENT JOINT (1 OF 11)
LATERAL SUPPORT FRAME

Figure 14. Heat exchanger coil assembly

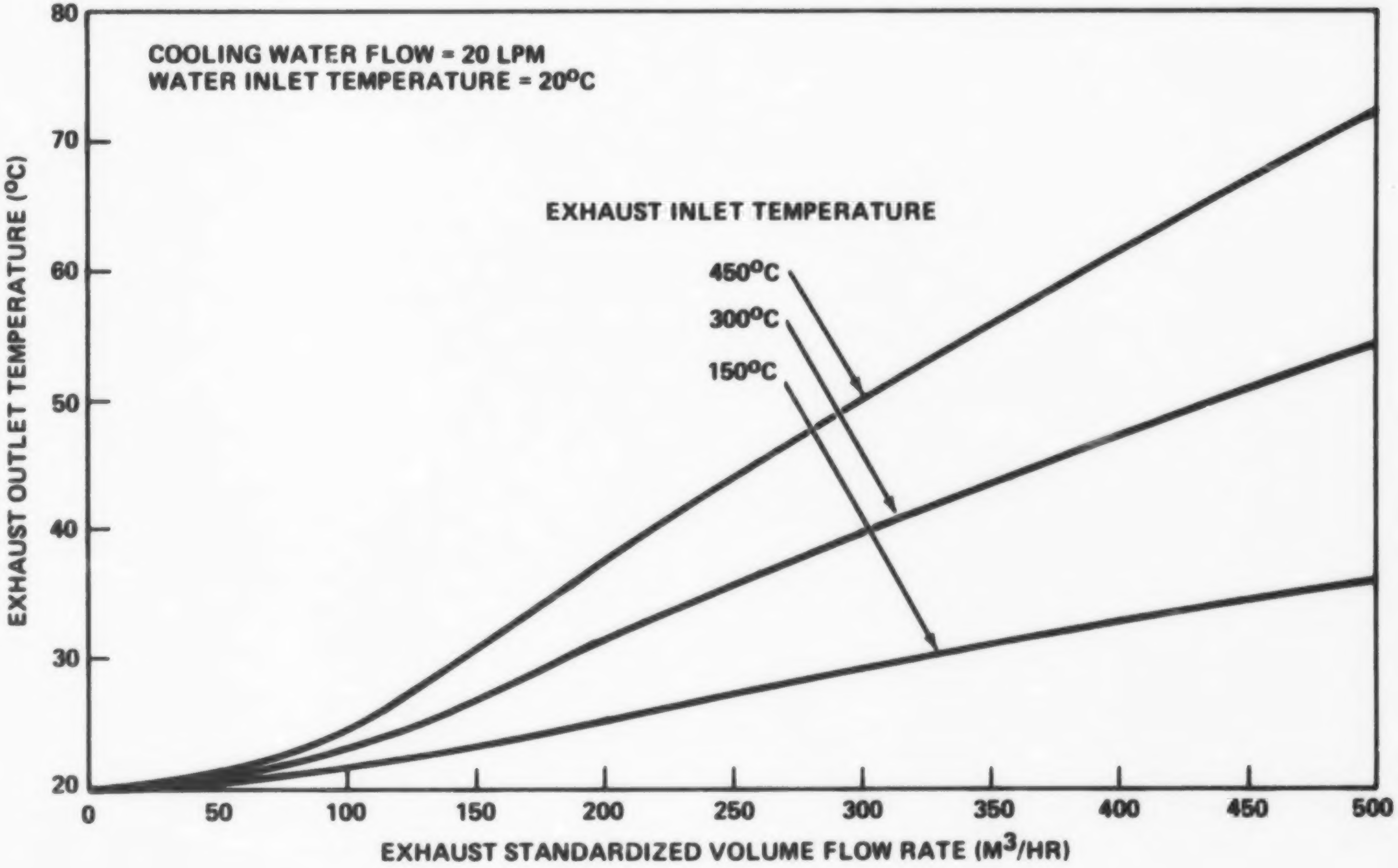


Figure 15. Heat exchanger performance estimate

SECTION 4

TEST RESULTS

The results of the exhaust flowmeter calibration, sample flow control valve calibration, and proportional sampler development testing are presented in this section.

FLOWMETER CALIBRATION

The flowmeter supplier, J-Tec Associates, provided an initial calibration obtained using a 0-680 m^3/hr laminar flow element (LFE). The objective of the subsequent calibration testing at Aeronutronic was to verify the J-Tec data, particularly in nonlinear flow ranges from 17 to 70 m^3/hr.

Three LFE's, with flow ranges of 0-34, 0-170, and 0-680 m^3/hr, were used in the calibration test setup shown schematically in Figure 16. Each LFE was placed in series with the vortex flowmeter to provide equivalent air mass flows through the two meters. The steady-state metered flow was adjusted by opening or closing the bypass butterfly valve. The critical flow venturi upstream of the vacuum-producing turbo-compressor provided an approximately constant sum of metered and bypass flows. The instrumentation was used to determine the vortex flowmeter's actual volume flow rate as a function of the vortex pulse frequency. The frequency was measured using several ten-second pulse counts for each flow setting. The instrumentation and ducting were thoroughly leak-checked prior to each series of tests.

During the series of tests with the 0-34 and 0-170 m^3/hr LFE's it was found necessary to modify the test setup slightly. Acoustic noise was being generated at the mixing point of the metered and bypass flows. This noise was of sufficient strength to interfere with the vortex shedding signal at the lowest metered flows. A plenum volume was inserted between the vortex flowmeter and the mixing point to attenuate the noise. This was successful to the point of eliminating all false pulses, even with the metered flow completely blocked off.

The calibration data finally obtained are presented in Figure 17, along with the data provided by J-Tec. The 0-34 and 0-680 agree reasonably well with the original calibration up to about 100 m^3/hr. Above that point the data diverge slightly to a maximum difference of 5 percent at

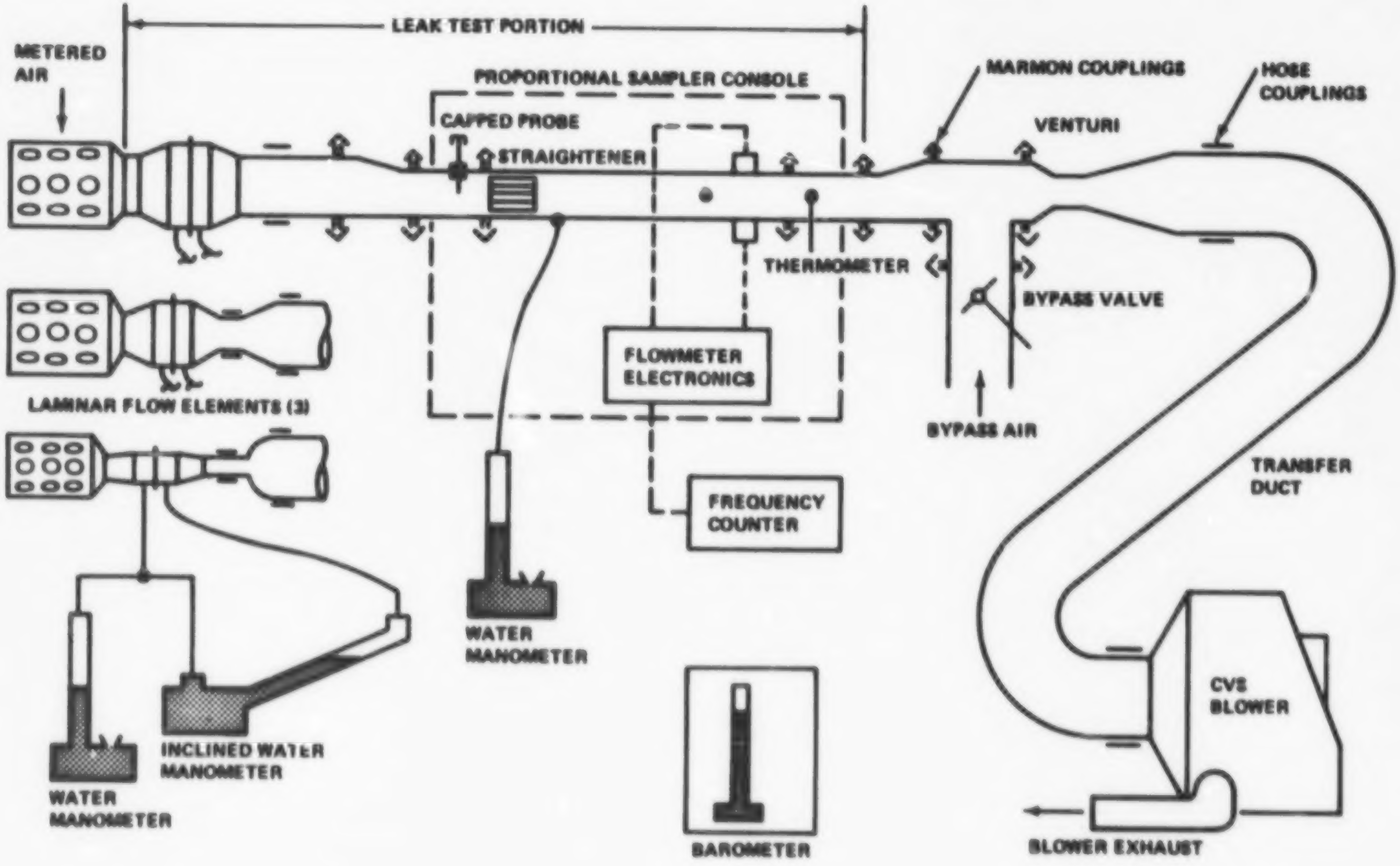

LEAK TEST PORTION
METERED AIR
PROPORTIONAL SAMPLER CONSOLE
CAPPED PROBE
STRAIGHTENER
MARMON COUPLINGS
VENTURI
HOSE COUPLINGS
THERMOMETER
BYPASS VALVE
BYPASS AIR
FLOWMETER ELECTRONICS
LAMINAR FLOW ELEMENTS (3)
FREQUENCY COUNTER
TRANSFER DUCT
WATER MANOMETER
CVS BLOWER
INCLINED WATER MANOMETER
WATER MANOMETER
BAROMETER
BLOWER EXHAUST

Figure 16. Exhaust flowmeter calibration test setup

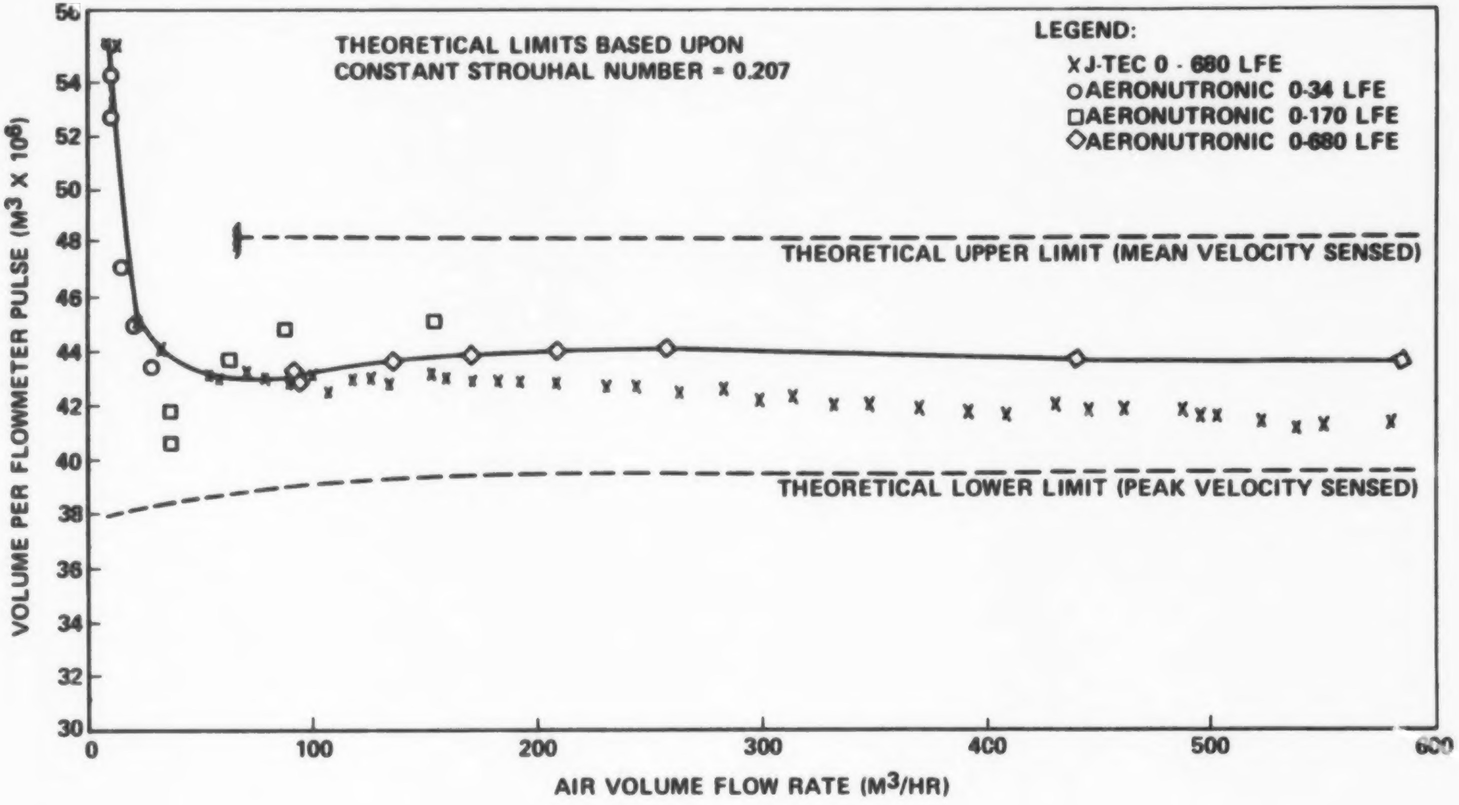


Figure 17. Exhaust flowmeter calibration data

600 m^3/hr. The 0-170 m^3/hr LFE did not produce consistent data in comparison with any other measurements. This LFE was judged to be out of calibration, and the data were not used. The final calibration curve employed for the vortex flowmeter is indicated in Figure 17. Also shown are the upper and lower theoretical calibration factor limits for a constant Strouhal number. These limits correspond to vortex shedding at the average and peak duct velocities respectively.

As discussed in the design of the signal processor, the flowmeter signal nonlinearity is appropriately characterized by determining the volume per pulse as a unique function of the parameter $\Delta t_m \, (T_1/T_S)^{1+\nu}$, termed the temperature-compensated flowmeter pulse interval. However, a complication arises in converting air flow calibration data for use in metering exhaust gas. This is due to differences in the dynamic viscosities of the two gases. The Reynolds numbers for air and exhaust flows will not be the same for equivalent values of the temperature-compensated pulse interval. Reynold's number equivalence can be obtained by an adjustment of the exhaust parameter:

$$[\Delta t_m \, (T_1/T_S)^{1+\nu}]_{exh} = [\Delta t_m \, (T_1/T_S)^{1+\nu}]_{air} \, \frac{(\mu_S)_{air}}{(\mu_S)_{exh}}$$

where: μ_S = gas dynamic viscosity at 20°C

air ∿ values for air flow

exh ∿ values for exhaust flow

The transport properties of air and exhaust were estimated using the methods of Reference 7 and the data of Reference 8. The results are presented in Table 5. These were used to obtain the value of the exhaust viscosity temperature exponent, ν, and the ratio of air/exhaust standard (20°C) viscosities. The flowmeter calibration data were then adjusted and converted to the functional format shown in Figure 18. The data of Figure 18 were then used directly in the programing of the read-only memory matrix for the signal processor.

It should be noted that the flowmeter nonlinearity and the viscosity correction factor are of generally reduced significance in the final proportional sampler configuration. This is because the heat exchanger precludes large values of T_1/T_S.

SAMPLE VALVE CALIBRATION

The purpose of the sample value calibration testing was to accurately determine the sample flow as a function of cycle frequency for a fixed

Table 5. EXHAUST GAS TRANSPORT PROPERTIES

Temperature (°K)	300	400	500	600	700
Specific Heat $(\frac{kJ}{kgm\ .\ ^\circ K})$	1.060	1.085	1.110	1.144	1.177
Dynamic Viscosity $(\frac{kgm}{m\ .\ S})$	1.653×10^{-5}	2.055×10^{-5}	2.421×10^{-5}	2.763×10^{-5}	3.083×10^{-5}
Thermal Conductivity $(\frac{kJ}{m\ .\ S\ .\ ^\circ K})$	2.528×10^{-5}	3.200×10^{-5}	3.860×10^{-5}	4.527×10^{-5}	5.180×10^{-5}
Prandtl Number	0.692	0.695	0.697	0.697	0.698

Notes: (1) Assumed combustion reaction is

$$0.1346\ CH_{1.85} + 0.938\ (0.78\ N_2 + 0.21\ O_2 + 0.01\ Ar)$$

$$\rightarrow 0.1346\ CO_2 + 0.1245\ H_2O + 0.7315\ N_2 + 0.0094\ Ar$$

(2) Air dynamic viscosity = 1.841×10^{-5} kgm/(m . S) at 300°K,
= 1.374 x exhaust viscosity at 300°K

(3) Viscosity temperature exponent $\approx$ 0.747

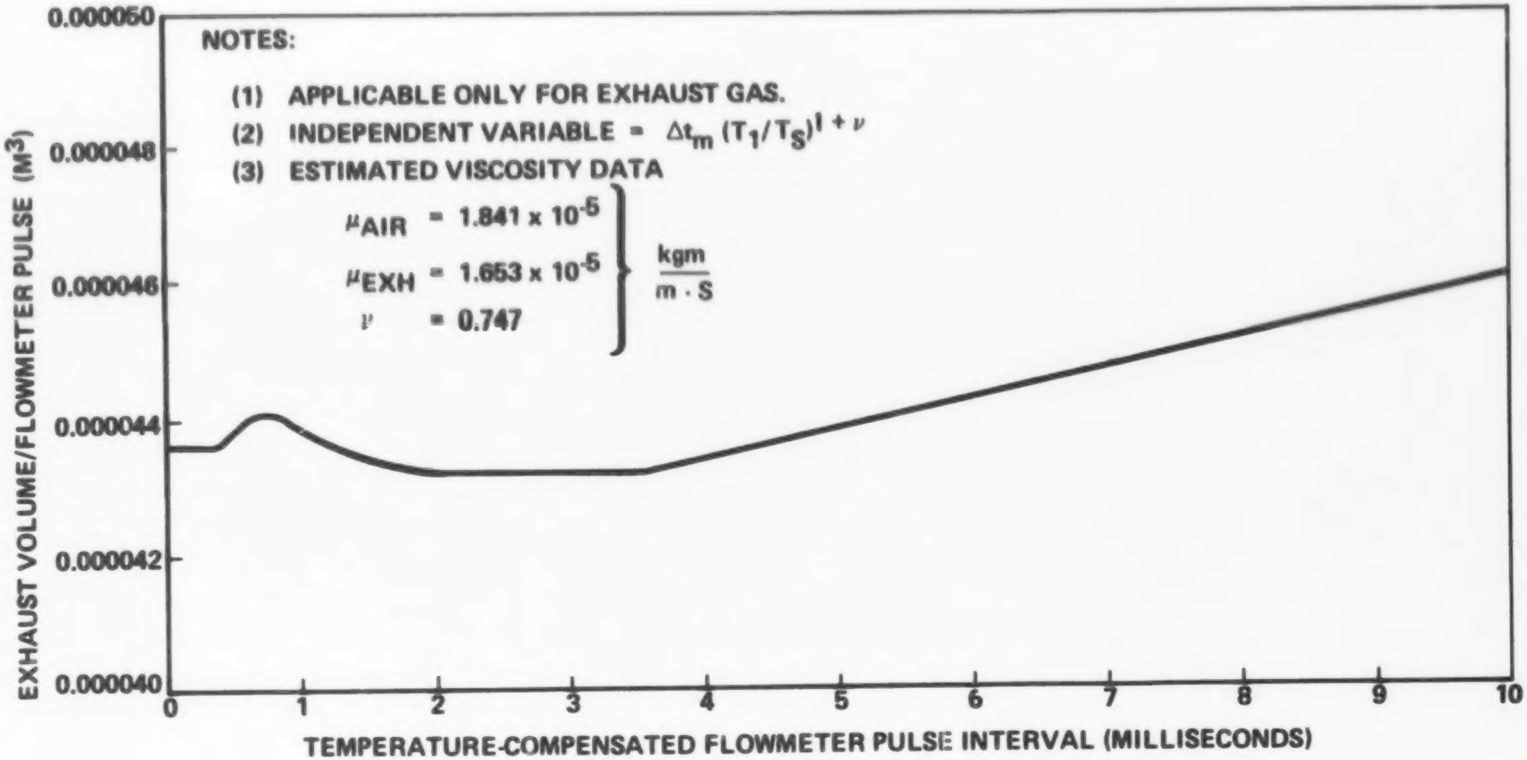


Figure 18. Flowmeter read-only memory function for the signal processor

valve-open interval. The data were checked for linearity and consistency with leakage and full-open flow measurements. The final calibration data permit evaluation of the sample flow proportionality constant, k.

The test setup is shown schematically in Figure 19. The method involved flowing a measured mass of dry air at a steady rate for a measured period of time. The parameters measured are indicated in Figure 19. The principal limit to the calibration accuracy is the scale resolution of 0.005 kgm. A minimum mass of air equal to 0.7 kgm was used for each test run to achieve an acceptable accuracy. The setup was leak checked with liquid leak detector at the beginning of each run.

The pump provided sufficient vacuum to insure choked flow across the valve orifice with a nominally atmospheric inlet pressure. The pressure/ vacuum gage and water U-tube manometer provided indication of the valve inlet pressure. The needle valve in parallel with the differential pressure regulator provided the final stage of regulation of the air flow. The needle valve was adjusted to maintain zero gage pressure at the valve inlet. Thus the valve inlet absolute pressure was simply the measured barometric pressure. The air-bottle pressure regulator provided an approximately constant input pressure to the flow regulator even though the air bottle pressure was continually decreasing. The heat exchanger coil allowed the air entering the flow regulator to be at a constant temperature during the run. The air temperature at the valve inlet was monitored using a thermocouple.

The sample valve coils were driven by the electronics used in the final proportional sampler assembly. Signal inputs were derived using available test equipment. Since coil temperature affects valve response, a cooling fan was used to stabilize the coil temperature. Approximately 5 minutes of 50 percent duty cycle warm-up were provided for the coils.

The above described setup was used to obtain data for 20, 30, and 40 Hz cycling rates, as well as for the full-open condition. For leakage measurements, however, this setup required impractically long run times. Instead, a low range rotameter (Brooks type 1110-01F1G1A, 0-0.85 lpm full-scale) was used to estimate the leakage flow rate.

The results of the calibration testing are summarized in Figure 20. First, two tests at the full-open condition were conducted to verify the repeatability of the setup. Then the three tests at the indicated cycling rates were performed. These data exhibited very good linearity, but did not agree with the results of numerous leakage tests. It appeared that the basic setup had a systematic error of about 0.34 lpm, which was independent of the flow rate. The source of this error could not be determined, but was probably associated with the bottle weight measurements. The final data were adjusted to agree with the leakage flow measuremen'.

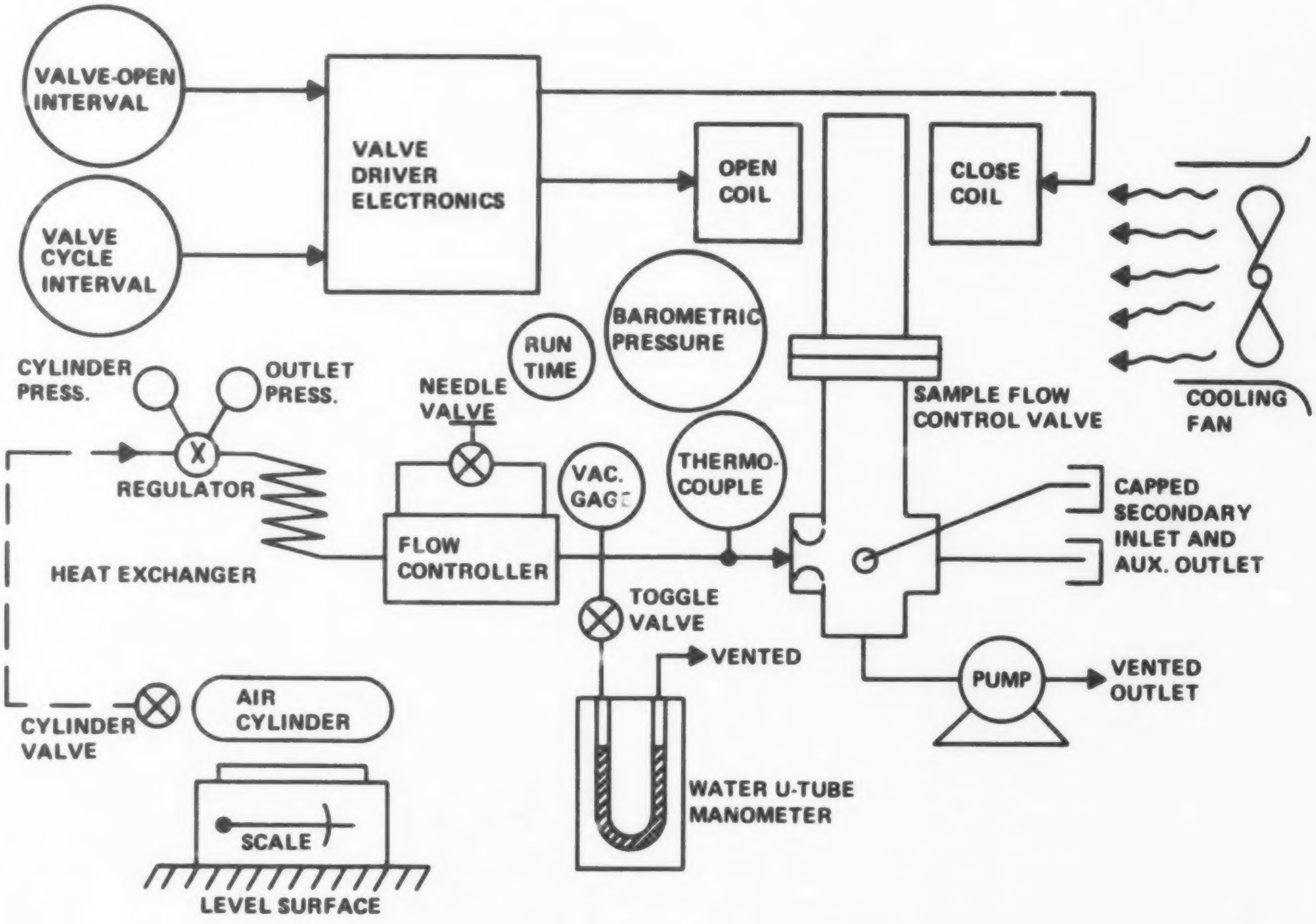

VALVE-OPEN INTERVAL
VALVE CYCLE INTERVAL
VALVE DRIVER ELECTRONICS
OPEN COIL
CLOSE COIL
COOLING FAN
RUN TIME
BAROMETRIC PRESSURE
SAMPLE FLOW CONTROL VALVE
CYLINDER PRESS.
OUTLET PRESS.
X
REGULATOR
HEAT EXCHANGER
NEEDLE VALVE
FLOW CONTROLLER
VAC. GAGE
THERMO-COUPLE
CAPPED SECONDARY INLET AND AUX. OUTLET
TOGGLE VALVE
VENTED
PUMP
VENTED OUTLET
CYLINDER VALVE
AIR CYLINDER
SCALE
LEVEL SURFACE
WATER U-TUBE MANOMETER

FIGURE 19. Test setup for sample valve calibration

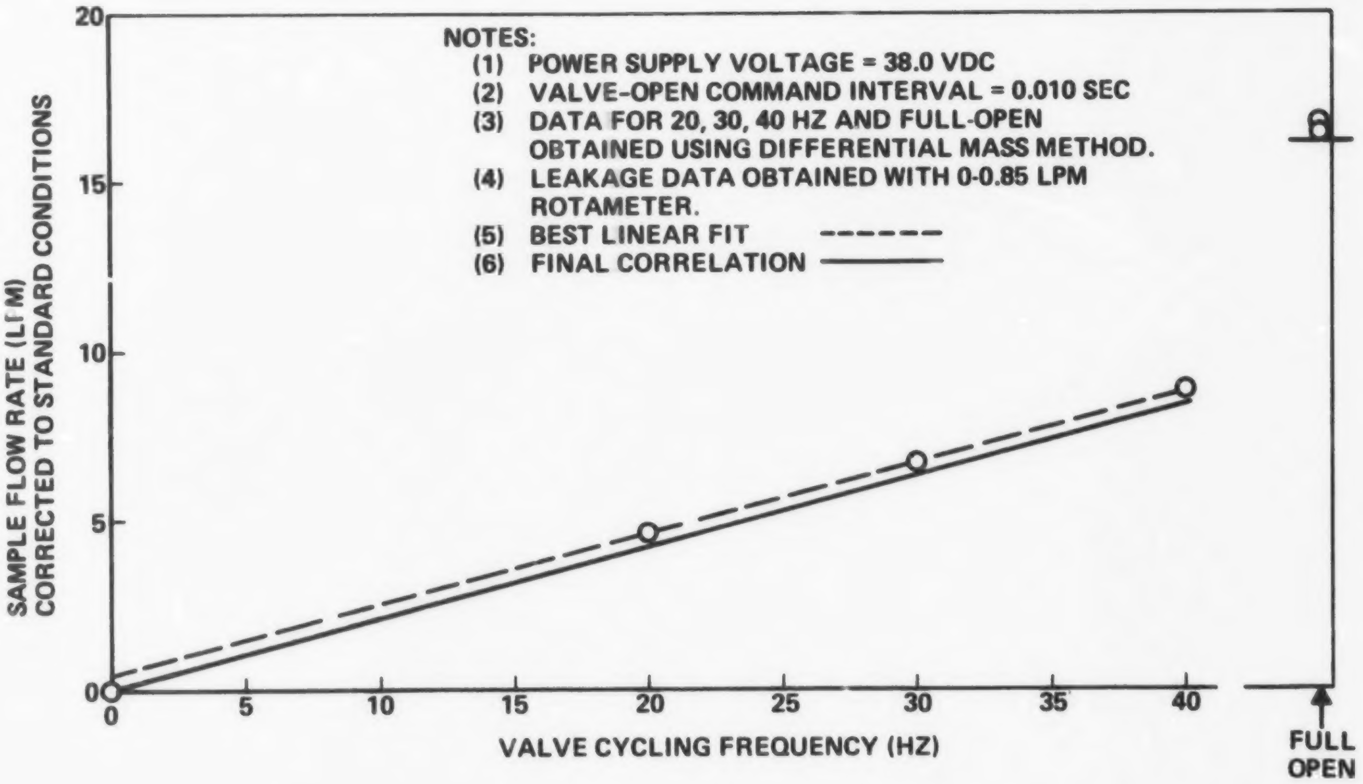


Figure 20. Sample valve calibration data

Using Equation 2 of Section III, the following valve parameters were then established as input constants to the signal processor:

(1) $t_o = 0.010$ second

(2) $\lambda_1 = 0.005$

(3) $\lambda_o = 1.297$

(4) $t_o (\lambda_o - \lambda_1) = 0.01292$ second

DEVELOPMENT TESTING

Testing of the proportional sampler was conducted in two phases. The initial phase had the primary objectives of (1) verifying the flowmeter accuracy for actual vehicle exhaust, (2) verifying the stability of the sample valve calibration after exposure to exhaust, and (3) evaluation of the flowmeter and sample valve durability in the exhaust environment. This phase was completed prior to the final configuration and integration of the signal processor, control panel, and sample flow system into the console. The second phase had the general objective of verifying the complete system's functional and performance characteristics. The results of these tests are presented in the following paragraphs, in essentially a chronological discussion.

Initial Test Phase

The development testing was conducted at the Aeronutronic Emissions Test Facility. The initial test setup is shown schematically in Figure 21. Two vehicles were used, one with a 6.55 liter V-8 engine and one with a 2.3 liter 4-cylinder in-line engine. The chassis dynamometer was a 45 kw electric type with inertial, grade, and road load simulation capabilities. The constant volume sampler (CVS) was an Aeronutronic Model CVS-4 with dilute exhaust temperature control and a critical flow venturi as the flow metering element. The gas analysis equipment included Beckman 315B CO_2 and CO analyzers and a Beckman Model 400 flame-ionization-detector (FID) for measurement of hydrocarbons (HC). These were housed in Aeronutronic Series 300 emissions analysis consoles which provided sample conditioning and electronic controls. Standard test equipment was used for all other measurements indicated in Figure 21.

During each test, whether steady-state or dynamic, a continuous sample of raw exhaust was drawn in parallel through the sample valve and a probe upstream of the CVS mixing point. This sample was partially dried in a refrigerated water bath prior to analysis for CO_2, CO, and HC volume fractions. Simultaneously, ambient and dilute exhaust samples were collected by the CVS as in a normal emissions test. These samples were then analyzed following completion of the test. Readings of exhaust duct pressure and flowmeter vortex frequency were manually recorded

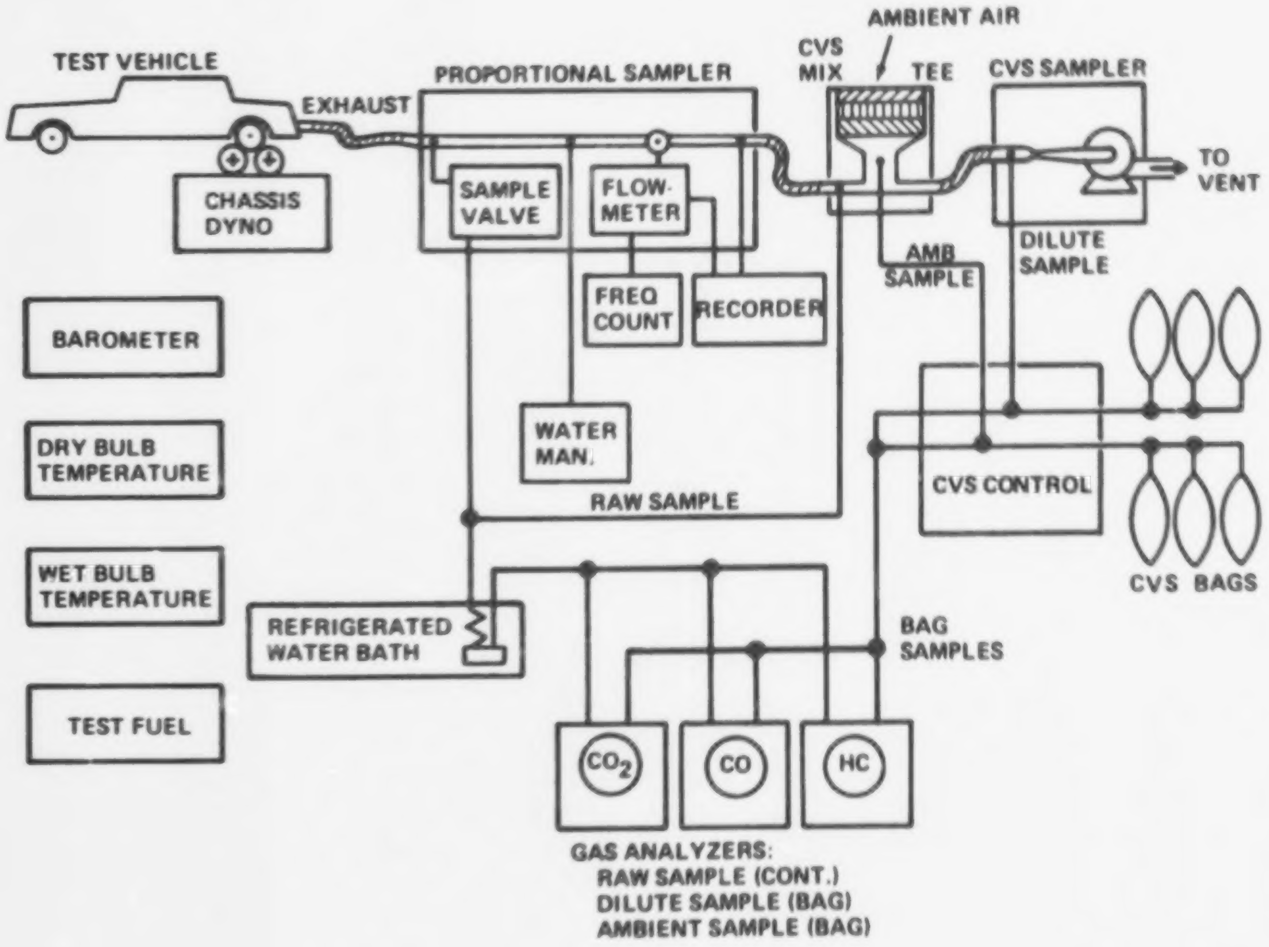

TEST VEHICLE
EXHAUST
CHASSIS DYNO
PROPORTIONAL SAMPLER
SAMPLE VALVE
FLOW-METER
FREQ COUNT
RECORDER
WATER MAN.
RAW SAMPLE
CVS MIX
AMBIENT AIR
TEE
AMB SAMPLE
CVS SAMPLER
DILUTE SAMPLE
TO VENT
CVS CONTROL
CVS BAGS
BAG SAMPLES
BAROMETER
DRY BULB TEMPERATURE
WET BULB TEMPERATURE
TEST FUEL
REFRIGERATED WATER BATH
CO2
CO
HC
GAS ANALYZERS:
RAW SAMPLE (CONT.)
DILUTE SAMPLE (BAG)
AMBIENT SAMPLE (BAG)

Figure 21. Proportional sampler development test setup

throughout each test. Exhaust duct temperature was measured continuously using a thermocouple and multi-point recorder. An analog signal of exhaust volume flow from the flowmeter was also recorded on a two-pen strip chart along with the vehicle speed signal.

For each test the standardized exhaust volume was calculated from the flowmeter data and compared with that calculated from the CVS data using a carbon balance method. A correction for the effects of sample drying was included in these calculations. The overall method is similar to that described in Appendix B of this report. The first tests conducted were with the V-8 engine at the steady-state conditions of loaded idle, 45 km/hr, 70 km/hr, and 85 km/hr. The standardized exhaust volumes from these tests, as indicated by the vortex flowmeter, were from 32 to 51 percent below those calculated from the CVS data. The 4-cylinder vehicle produced an obviously anomalous flowmeter signal prior to conduct of formal tests.

A four-trace oscillscope was used to monitor the flowmeter's internal electronic signals. The principal signals of interest were the amplitude-modulated ultra-sonic carrier signal, the demodulated audio frequency vortex shedding signal, and the digital pulse output signal. The vortex shedding signal appeared to have a strong interference pattern, indicating a second source of modulation for the ultrasonic beam in addition to the vortex-shedding process. The consequent irregular nature of the signal led to so-called pulse-dropping in the output signal. This was caused by the inability of the pulse-triggering electronics to discriminate between the two modulation sources. Consultation with the flowmeter supplier led to modification of the electronic signal filter parameters. In effect this resulted in a narrower bandpass for the input to the pulse-triggering electronics. However, the spectrum of the spurious modulation source overlapped the vortex shedding bandpass such that significant interference and pulse-dropping remained.

It was suspected that the secondary modulation source was the presence of pressure waves in the flowmeter duct. These were thought to be caused by noise and exhaust manifold pressure fluctuations which were not sufficiently attenuated by the vehicle's muffler. This hypothesis was confirmed in a series of tests to develop a supplementary acoustic muffler configuration. A variety of experimental configurations were evaluated including:

(1) A second automobile muffler in series with either a 208 liter or a 416 liter plenum tank.

(2) A butterfly valve in series with either a 208 or 416 liter plenum tank.

(3) A small diameter (4.5 cm) inductance tube in series with either a 208 or 416 liter plenum tank.

In all cases the flowmeter signal quality was significantly improved. A comparison of the flowmeter signals between unmuffled and muffled exhaust flow is provided in Figure 22. The four traces, beginning with the topmost, are the modulated carrier (shown as a half-wave in parts b and c), the demodulated vortex shedding signal, the corresponding output pulse train, and the pressure in the flowmeter duct. This last trace was obtained using strain-gage diaphragm pressure tranducer.

Part (a) of Figure 22 illustrates the effect of severe engine pulsations (rough idle) on the flowmeter signals. The strong pressure waves scatter the ultra-sonic beam with nearly 100 percent modulation of the carrier signal, thus swamping the vortex shedding modulation. The result is extensive intermittent pulse dropping (gaps) in the output pulse train. Part (b) illustrates a more typical level of pressure pulsation, but still with a significant percentage of pulse-dropping in the output signal. Note that although the basic vortex shedding frequency can be visually determined from the photograph, the pulse-triggering electronics can only detect a zero-crossing of the demodulated signal.

Part (c) of Figure 22 shows the effect of an order-of-magnitude reduction in pressure pulsation magnitude at the flowmeter. (The pressure trace voltage scale is 10 percent of that for parts (a) and (b).) The demodulated signal is relatively regular and very few pulses are lost in the output signal. This particular muffler arrangement included a second automobile muffler as well.

Tests using the first 505 seconds of the EPA Urban Driving Schedule finally yielded very good agreement (less than 0.5 percent error) between the flowmeter and CVS-derived standardized exhaust volumes. Further tests were then conducted to determine an optimum configuration for a permanent supplemental muffler.

The muffler tests showed the plenum tank volume and downstream inductance to be the most important parameters. This arrangement is analogous to a parallel L-C electrical low-pass filter circuit in that the input noise spectrum is attenuated above a cutoff frequency:

$$f_c \sim D\sqrt{T_1/(V_T \ell)}$$

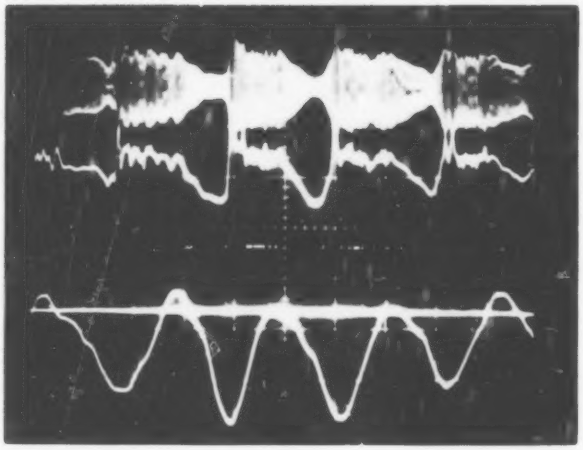
where: D = inductance tube diameter (m)

T_1 = gas temperature (°K)

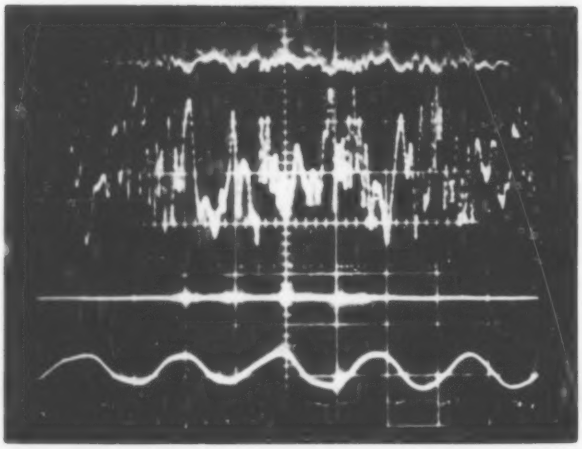
V_T = plenum tank volume (m^3)

ℓ = inductance tube length (m)

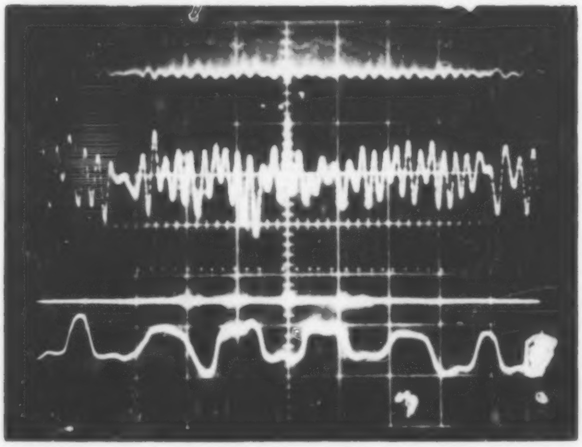
The desire to minimize this frequency was balanced by the need to maintain a low exhaust pressure loss through the ducting, and practical limits on the plenum tank volume. There was also concern over maintaining a time-correlated sample with the dynamically varying exhaust flow. This led to incorporation of the plenum tank downstream of the sample probe, such



(A) NO PLENUM VOLUME. SEVERE ENGINE PULSATION. PEAK-TO-PEAK PRESSURE ≈ 4.0 KPA



(B) NO PLENUM VOLUME. NORMAL ENGINE PULSATION. PEAK-TO-PEAK PRESSURE ≈2.7 KPA



(C) PLENUM VOLUME ≈416 ℓ. NORMAL ENGINE PULSATION. PEAK-TO-PEAK PRESSURE ≈ 0.2 KPA

Figure 22. Comparison of vortex flowmeter signals (varying plenum volume)

that the transport delay of exhaust from the tailpipe to the sample probe is minimized. The final configuration, described in the preceding section, included a 237 liter plenum volume with any one of six 1.2 m long inductance tubes. The tube inside diameters ranged from 3.8 cm up to the full diameter of the flowmeter duct, 7.29 cm. The corresponding cutoff frequencies were from 9 to 17 Hz. These are substantially less than the lowest vortex frequency of interest, 100 Hz. Interchangeable tubes were provided to permit trade-off of the cutoff frequency for reduced exhaust pressure loss.

In addition to this primary result of the initial development testing, the following durability results were obtained:

(1) The sample valve leakage and full-open flows were remeasured and found to be identical to their original values.

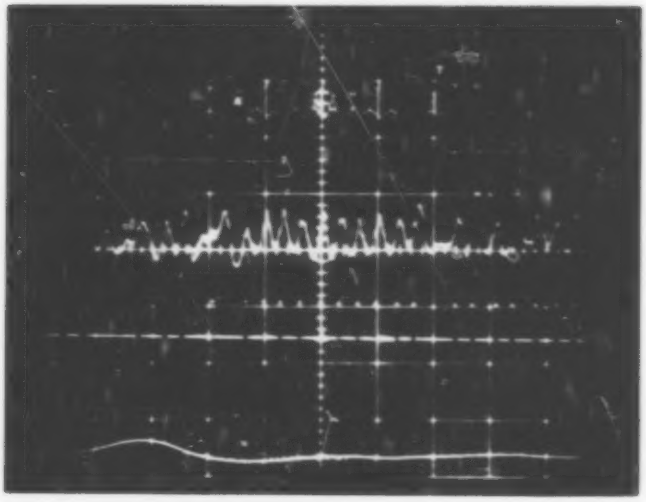
(2) The stainless steel prefilter element had become clogged, indicating a need to occasionally clean or replace the element. A 50 μm pore size was substituted for the original 15 μm element.

(3) The aluminum honeycomb material used in the flowmeter to collimate the ultrasonic beam within the transmitter and receiver cavities had become significantly corroded in the high temperature exhaust environment. They were subsequently replaced with collimators made from stainless steel honeycomb. This apparently straightforward substitution led to a further development problem discovered in the second phase of testing.

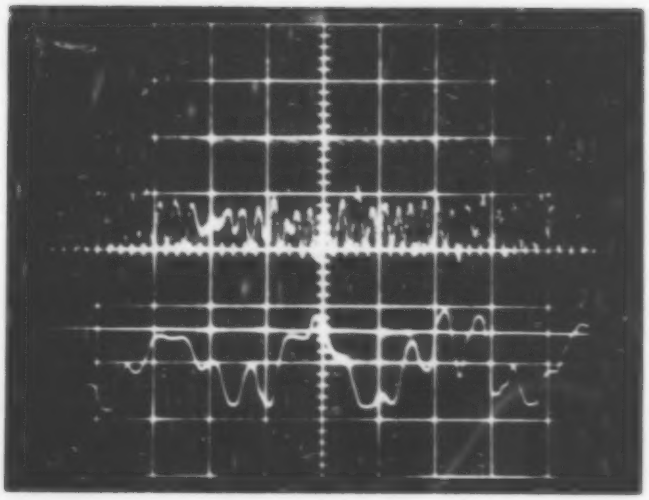
(4) The above-mentioned collimators tended to accumulate condensed water vapor from the exhaust. In one case this obstructed the ultrasonic beam sufficiently to affect the flowmeter signal quality. This is illustrated in Figure 23, where the reduced amplitude of the carrier is apparent. The flowmeter electronics include compensation for variations in carrier signal strength, but in this case the compensation circuitry had become saturated. This would have been a minor problem in the original configuration, and the use of an exhaust heat exchanger virtually eliminated it altogether.

Final Test Phase

The setup for the final phase of testing was similar to that for the initial phase, but with the completely assembled proportional sampler. The basic test plan for the final tests was the EPA Evaluation Test Plan (Appendix B). The principal performance objective was agreement



(A) BEFORE CLEANING AND DRYING OF ALUMINUM HONEYCOMB COLLIMATORS. (WEAK CARRIER SIGNAL)



(B) AFTER CLEANING AND DRYING OF COLLIMATORS. (NORMAL CARRIER SIGNAL)

Figure 23. Effect of acoustic beam obstruction on flowmeter signals

between the proportional sampler and the CVS for CO_2 and CO mass emissions. The CO_2 mass would primarily reflect accurate exhaust flow metering, while the CO mass in conjunction would reflect accurate sample proportioning by the signal processor and sample valve. The test setup included the Aeronutronic Model CVS20 and advanced prototype analysis equipment, as well as the previously used analyzers.

The first tests of this phase revealed flow metering errors in the range of 10 to 30 percent compared to the CVS values. Monitoring of the flowmeter signals led to the discovery of an abnormal carrier signal waveform. This is illustrated in Figure 24, and was the effect of the changed beam collimators. The flowmeter was then returned to J-Tec for repair and readjustment, with the following results:

(1) One of the ultrasonic transducers was found to be faulty, and was replaced.

(2) The stainless steel collimators were replaced by slightly longer (2.54 cm versus 1.78 cm) stainless steel honeycomb pieces. Although not as long as the original aluminum pieces (3.8 cm), the carrier signal quality was acceptable (Figure 24).

(3) The transducer orientations and ultrasonic beam (i.e., carrier) frequency were readjusted to obtain good signal quality for air flow in the range from 17 to 500 m^3/hr.

After reinstallation of the flowmeter, steady-state tests with vehicle exhaust continued to result in flowmeter pulse dropping and consequent mass emissions errors of up to 28 percent. A series of tests were then conducted to isolate the cause of the acoustic beam secondary modulation. This included use of the special duct pressure transducer, retest of prior experimental muffler configurations, and evaluation of alternate muffler approaches. The results were as follows:

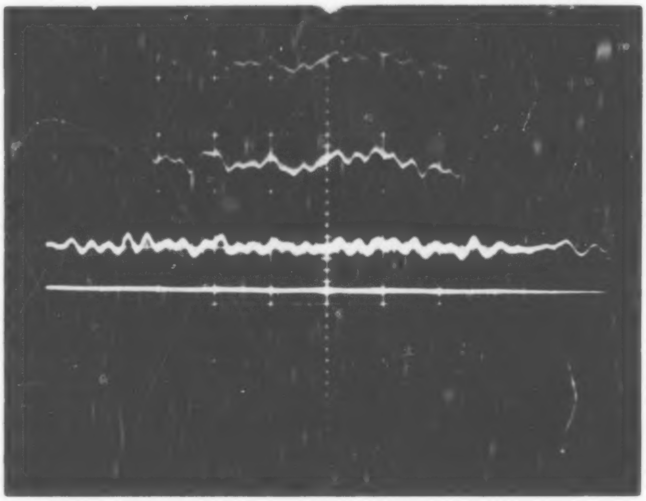
(1) The flowmeter tended to perform best at idle flows, indicating satisfactory attenuation of the lowest engine pulsation frequencies.

(2) The experimental muffler arrangements provided better flowmeter accuracy than the permanent muffler, indicating the importance of muffler shape as well as plenum volume.

(3) An experiment with a sound absorbent liner in the plenum tank reduced the flowmeter errors by more than half.

From these tests it appeared necessary to modify the muffler to further attenuate pressure fluctuations in the flowmeter duct. The source of these fluctuations was thought to be standing pressure waves in the

(A) SHORT (1.78 CM) STAINLESS STEEL HONEYCOMB COLLIMATORS. (NOTE ASYMMETRIC MODULATION OF CARRIER SIGNAL.)



(B) MEDIUM (2.54 CM) LENGTH STAINLESS-STEEL HONEYCOMB COLLIMATORS. (NOTE NORMAL SYMMETRIC MODULATION OF CARRIER SIGNAL.)

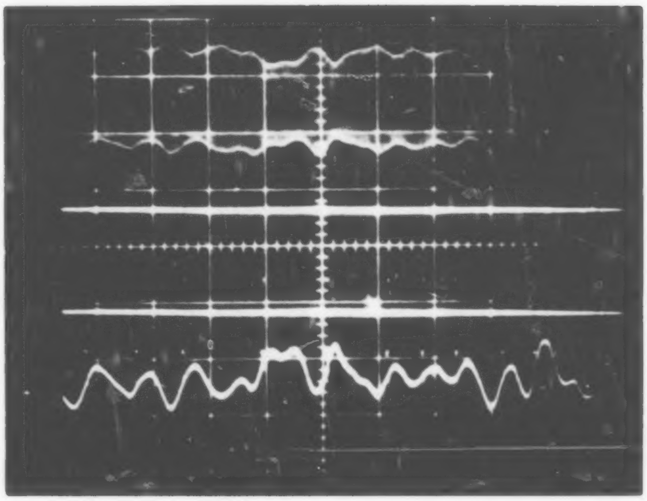


Figure 24. Effect of acoustic beam collimators length on flowmeter signals

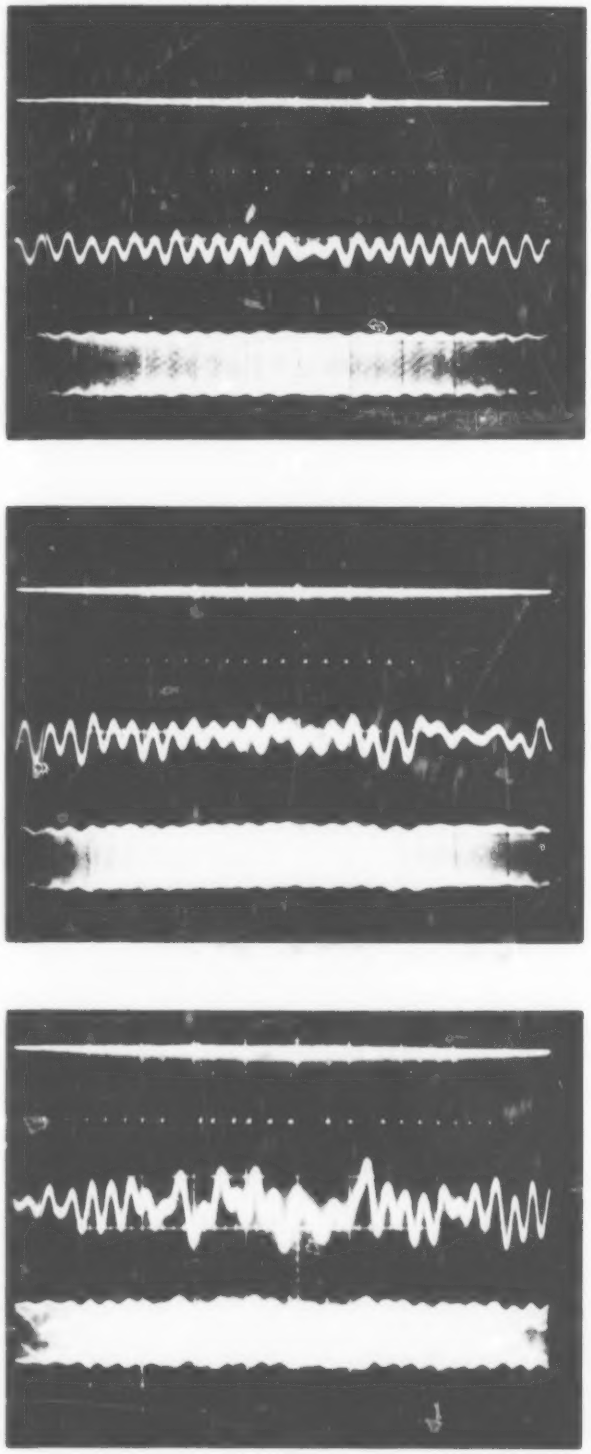
plenum tank at frequencies corresponding to the second and higher harmonics of the longitudinal wavelength. Analyses indicated the desireability of using an absorbent liner in the tank. A fiberglass material suitable for the high temperature exhaust environment was obtained and installed.

Two series of three 505 second (transient phase of the EPA Urban Driving Schedule) dynamic tests were conducted, one with and one without the plenum tank liner. Both series of tests involved the following sequence — cold start 505, 10-minute vehicle soak with the ignition off, warm start 505, and a final hot start 505 cycle with no vehicle soak. The results were clear trends of increasing error from cold to warm to hot cycles, and from the unlined to lined plenum tank. This led to the hypothesis that the flowmeter signal was at least partially affected by the exhaust temperature.

A test of this hypothesis was conducted using a resistance heater in conjunction with an ambient air flow. Gas temperatures of 65°C and 122°C were obtained using 115 and 208 volt AC power, respectively. The results were as illustrated in Figure 25. It can be seen that the remaining secondary modulation source is due to the elevated gas temperature. The modulation mechanism is not clear, but probably involves thermal turbulence (waves) in the hot flow, or possibly beam reflections due to temperature gradients along the beam axis. Attempts to resolve the physical phenomena involved were not pursued since a more direct solution of the problem appeared feasible.

The most obvious approach to the problem was the incorporation of an exhaust heat exchanger in the plenum tank. A test of this approach was conducted using an available commercial water/air heat exchanger. The exchanger was located between the tailpipe and the plenum tank inlet. An ambient-temperature water flow of 20 l/m provided an exhaust temperature reduction of up to 160°C as the gas temperature at the flowmeter was kept below 50°C. The resulting flowmeter signal quality was excellent, implying that the signal interference problem experienced in the second phase of testing was due solely to gas temperature effects. Comparisons of the cooled and uncooled exhaust flowmeter signals are provided in Figures 26 and 27.

Following this test the detailed design, fabrication, and installation of the final exhaust heat exchanger was completed. Final tests of the proportional sampler resulted in good agreement for the CO_2 (average error of 0.7 percent for six tests) and CO (average error of 3.8 percent for three tests) mass emissions in comparison with the CVS. The heat exchanger performance was as predicted, with the exhaust temperature maintained below 35°C. However, the exhaust pressure loss was higher than desired. Tests with ambient air indicated an overall loss of 1.25 kP_a at a flow of 265 m^3/hr. This will be acceptable for testing of light duty vehicles in the current emissions and fuel economy driving schedules. The peak exhaust flow occurs in the second cycle of the Urban Driving Schedule. A typical dynamic exhaust flow histor, (as

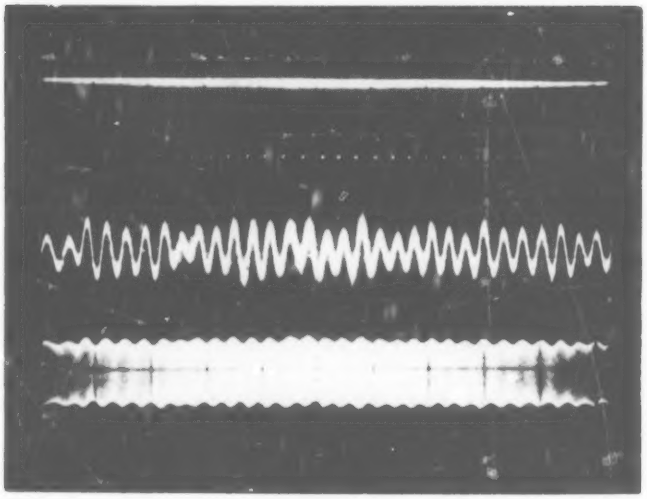


(A) $T_1 = 20^oC$
$Q_A \approx 75\ M^3/HR$
DROPPED PULSES <0.5%

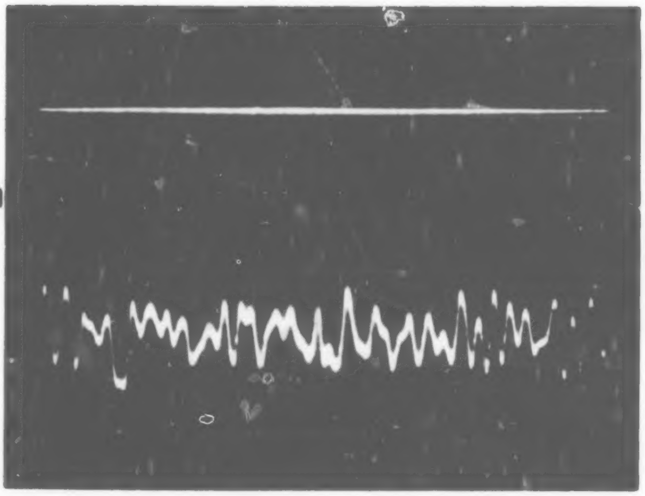
(B) $T_1 = 65^oC$
$Q_A \approx 75\ M^3/HR$
DROPPED PULSES ≈ 1.0%

(C) $T_1 = 122^oC$
$Q_A \approx 75\ M^3/HR$
DROPPED PULSES ≈ 12.5%

Figure 25. Comparison of flowmeter signals for heated air flows



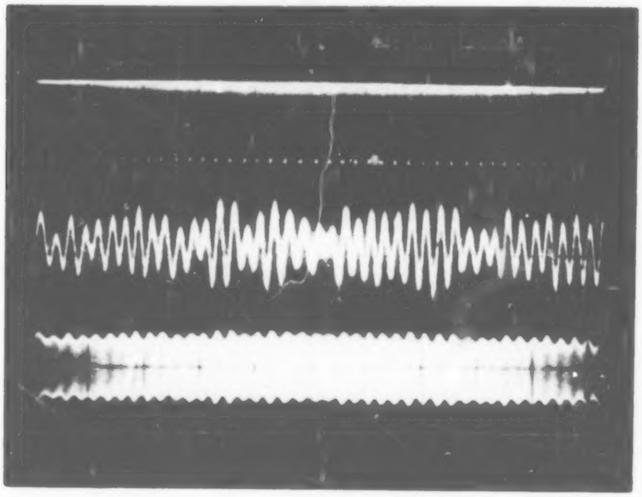
(A) WITH HEAT EXCHANGER INSTALLED.
$T_1 < 35^{\circ}C$
$Q_A \approx 95\ M^3/HR$



(B) PRIOR TO INSTALLATION OF HEAT EXCHANGER
$T_1 \approx 130^{\circ}C$
$Q_A \approx 90\ M^3/HR$

Figure 26. Comparison of flowmeter signals for vehicle exhaust flow (cruise condition)

(A) WITH HEAT EXCHANGER INSTALLED.
$T_1 < 35^oC$
$Q_A \approx 125 M^3/HR$



(B) PRIOR TO INSTALLATION OF HEAT EXCHANGER.
$T_1 \approx 150^oC$
$Q_A \approx 140 M^3/HR$

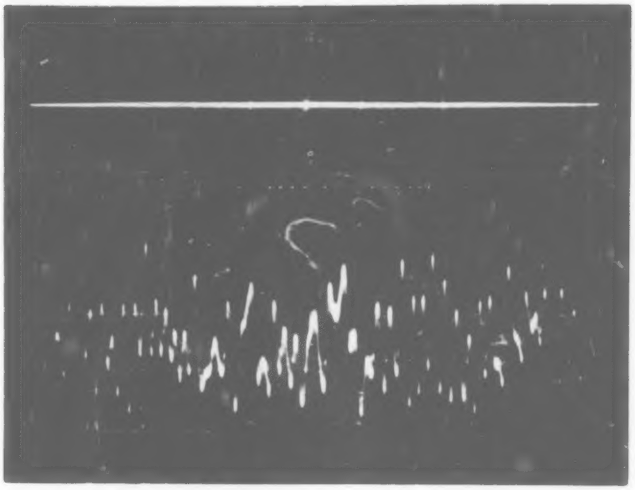


Figure 27. Comparison of flowmeter signals for vehicle exhaust flow (acceleration condition)

traced from a strip chart with reversed time scale), is shown in Figure 28 for this cycle. Note that peak flows always occur during acceleration modes, which by their nature are of limited duration. As a cruise mode is entered the flow will be reduced, and will decline to nearly the idle flow during deceleration modes. The largest engines may exceed the tailpipe pressure disturbance at about 195 seconds into the urban driving schedule, but the duration of this excursion will certainly be less than 2 seconds.

After completion of the second phase of development testing at Aeronutronic, the device was shipped to the EPA Triangle Park facility, along with complete operating and maintenance instructions. The proportional sampler was installed and performed satisfactorily in preliminary evaluation testing. Included in these tests were vehicles equipped with oxidation catalysts which produce exhaust temperatures up to 450°C.

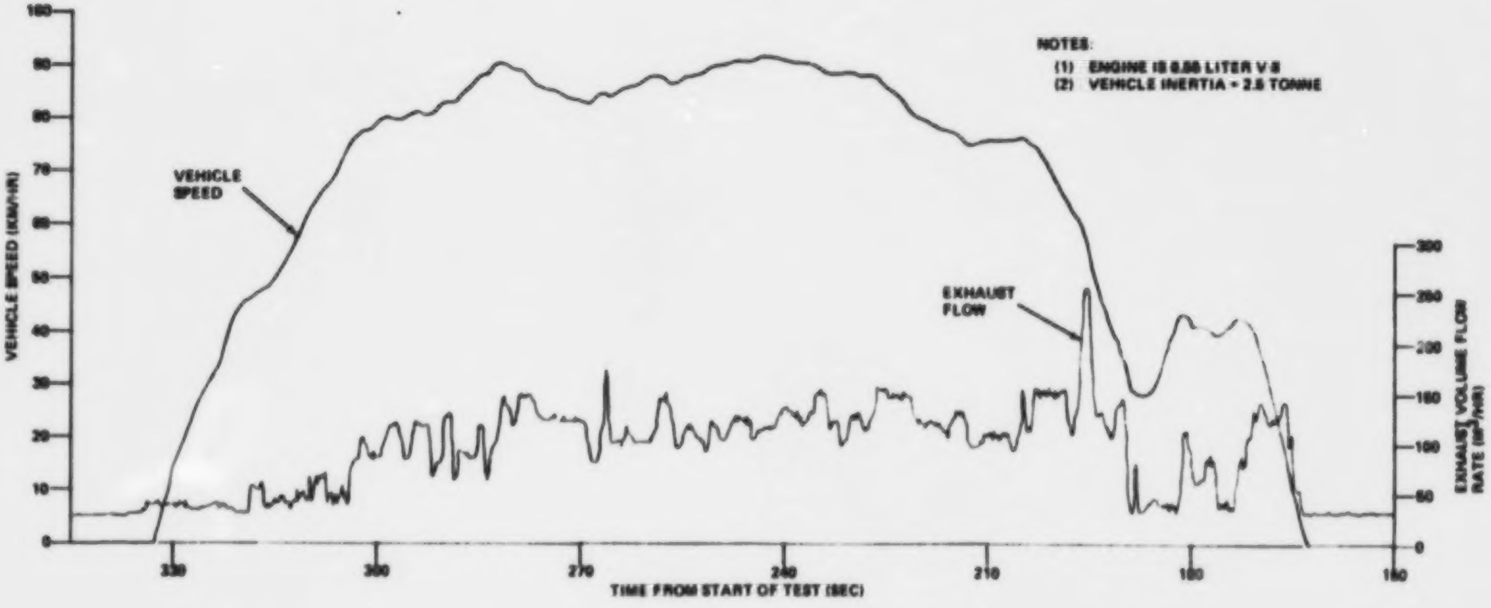


Figure 28. Typical exhaust flow trace over a complete cycle of the EPA urban driving schedule

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APPENDICES

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APPENDIX A

PROPORTIONAL SAMPLER
FOR AUTOMOBILE EXHAUST EMISSIONS TESTING
SPECIFICATION OF REQUIREMENTS

1.0 SCOPE

Specified herein are the functional, performance, and critical component requirements for a Proportional Sampler (hereafter called "device"). The purpose of the device is to permit determination of specie masses emitted in the exhaust of an internal combustion engine during a simulated road test on a dynamometer. In this context the principle function of the device is to collect and hold for analysis an exhaust sample drawn at a mass flow rate in constant, known proportion to the instantaneous total exhaust mass flow rate.

2.0 FUNCTIONAL REQUIREMENTS

2.1 General

The device shall sample the engine exhaust at a mass flow rate in constant proportion to the total exhaust mass flow rate at all normal engine operating modes. Sampling proportionally shall be maintained throughout the EPA Urban Driving Schedule (LA-4-S-3, as specified in the Federal Register, Vol. 37, No. 221, dated Wednesday, November 15, 1972), including idle, acceleration, cruise, and deceleration modes. The device shall not dilute the exhaust sample in any manner.

2.2 Exhaust Flow Metering

The device shall directly meter the flow of total engine exhaust. The instantaneous flowmeter signal shall be used to control the sample flow regulating component (i.e., sample flow control valve) and to determine the cumulative exhaust mass emitted during the test.

2.3 Exhaust Flow Conditioning

The device shall include all components to condition the exhaust flow as required to assure acceptable flow metering accuracy. Such components may include straightening vanes, acoustic mufflers, heat exchangers, or other items as necessary.

2.4 Sample Conditioning

The device shall provide for the following sample conditioning functions:

(a) Extraction of the sample gas from the exhaust stream without entrainment of particulates.

(b) Removal of water vapor and heavy hydrocarbons from the sample.

(c) Maintenance of the sample temperature at or above 90°C between the point of extraction and the condensate trap.

(d) Filtering of fine particle contaminates from the sample.

(e) Pumping of sample through the conditioning system into the collection bag.

(f) Collection of the sample flow so that a mass-weighted average sample is obtained for the test. The collection bag shall be sufficient to hold the entire volume of sample from an LA-4-S-3 test. A total of three collection bags shall be provided for use in tests involving three-phase (cold transient, stabilized, hot transient) driving schedules. Transfer of a sample to an analysis system shall be permitted simultaneous to the filling of any other bag with sample.

2.5 Sampling Components Purge

The device shall provide for ambient air purge of the sample extraction probe, condensate trap, and sample collection bags. Evacuation of purge air from the collection bags shall also be provided.

2.6 Durability

The device shall be capable of handling undiluted internal combustion engine exhaust at gas temperatures up to 450°C. Only stainless steel or Teflon or materials of equivalent durability shall be exposed to the exhaust and sample gases.

2.7 Control and Data Display

The device shall provide for manual operation and data acquisition. In addition, the three-phase sample collection procedure shall be capable of being implemented with a single start command, at either the control panel or at a remote station. The device shall provide the following data at the control panel:

(a) Visual readout of cumulative exhaust mass for each of three test phases.

(b) Visual monitoring of operating parameters including exhaust pressure and temperature, sample pressures and temperatures, exhaust volume and mass flow rates, and sample flow control valve duty cycle.

(c) Analog signals for external recorders including exhaust volume and mass flows, exhaust pressure and temperature, and sample flow control valve inlet temperature and duty cycle.

3.0 PERFORMANCE REQUIREMENTS

3.1 Exhaust Flow

The device shall be capable of operation over the range of exhaust volume flow from 17 to 500 m^3/hr and the range of exhaust temperature from 5°C to 450°C.

3.2 Sample Flow

The maximum obtainable sample flow shall be a minimum of 8.5 lpm. The sample flow proportionality constant shall be selectable from the following nominal values:

(a) 3.00 parts/thousand (ppk) for 170 m^3/hr peak exhaust flow.

(b) 2.00 ppk for 255 m^3/hr peak exhaust flow.

(c) 1.70 ppk for 300 m^3/hr peak exhaust flow.

(d) 1.50 ppk for 340 m^3/hr peak exhaust flow.

(e) 1.33 ppk for 380 m^3/hr peak exhaust flow.

(f) 1.20 ppk for 425 m^3/hr peak exhaust flow.

(g) 1.00 ppk for 510 m^3/hr peak exhaust flow.

(h) 0.75 ppk for 680 m^3/hr peak exhaust flow.

3.3 Accuracy

The device shall provide the following accuracies over the operating ranges specified above.

(a) Sample proportionality constant within ±2 percent of specified value.

(b) Cumulative exhaust readout within ±1 percent of value. (Above 0.3 m^3.)

(c) Analog recorder signals within ±1 percent of full scale values.

3.4 Response

The device shall meet the following dynamic response criteria.

(a) Ducting hold-up volume less than 0.25 m^3 between the inlet and the exhaust flowmeter, including acoustic muffler, but not including ducting from the engine to the muffler inlet.

(b) Response to step change in exhaust flow rate:

$$\tau_{flow} \leq 0.01 + 0.025\ Q_{peak}/Q_{final}$$

where

τ_{flow} = equivalent low-pass (dissipative) filter time constant (seconds)

Q_{peak} = selected peak exhaust flow (170, 255, 300, 340, 380, 425, 510, 680 m^3/hr)

Q_{final} = exhaust flow rate following the step change (m^3/hr)

(c) Response to step change in exhaust temperature:

$$\tau_{temp} \leq 1.4\ (17/Q)^{1/2}$$

where:

τ_{temp} = equivalent low-pass (dissipative) filter time constant (seconds)

Q = exhaust flow rate (m^3/hr)

3.5 Exhaust Back-Pressure

The exhaust pressure drop through the device shall not exceed 1.240 KP_a including losses due to flow conditioning.

4.0 COMPONENT REQUIREMENTS

4.1 Exhaust Flowmeter

The exhaust flowmeter employed in the device shall be of the vortex shedding type, and shall use an ultrasonic beam scattering technique for quantitative detection of the vortex shedding frequency. The flowmeter shall satisfy the following performance criteria:

(a) Flow range from 17 to 500 m^3/hr.

(b) Calibration as shown in Figure 1.

(c) Nonlinearity of calibration less than 10 percent of value at any point in the flow range.

(d) Nonrepeatability less than ±1/2 percent of value at any point in the flow range (based on 100 pulse count interval).

(e) Negligible dynamic distortion for flow variations at frequencies less than 1 Hertz per m^3/hr over the flow range.

(f) Pressure drop less than 0.375 KP_a at 680 m^3/hr.

4.2 Sample Flow Control Valve

The sample flow control valve used in the device shall be a frequency modulated on/off type. The valve shall incorporate a critical flow orifice to meter the sample flow, and a solenoid driven flapper to open and close the orifice. The valve shall satisfy the following performance criteria:

(a) Full-open flow of at least 16.2 lpm for an inlet temperature and pressure of 20°C and 101.325 KP_a absolute, respectively.

(b) Full-closed (leakage) flow less than 1/2 percent of the full-open flow value.

(c) Calibration as shown in Figure 2.

(d) Negligible nonlinearity and nonrepeatability of calibration for input frequencies up to 40 Hertz, with an input valve-open command of 10.0 msec duration.

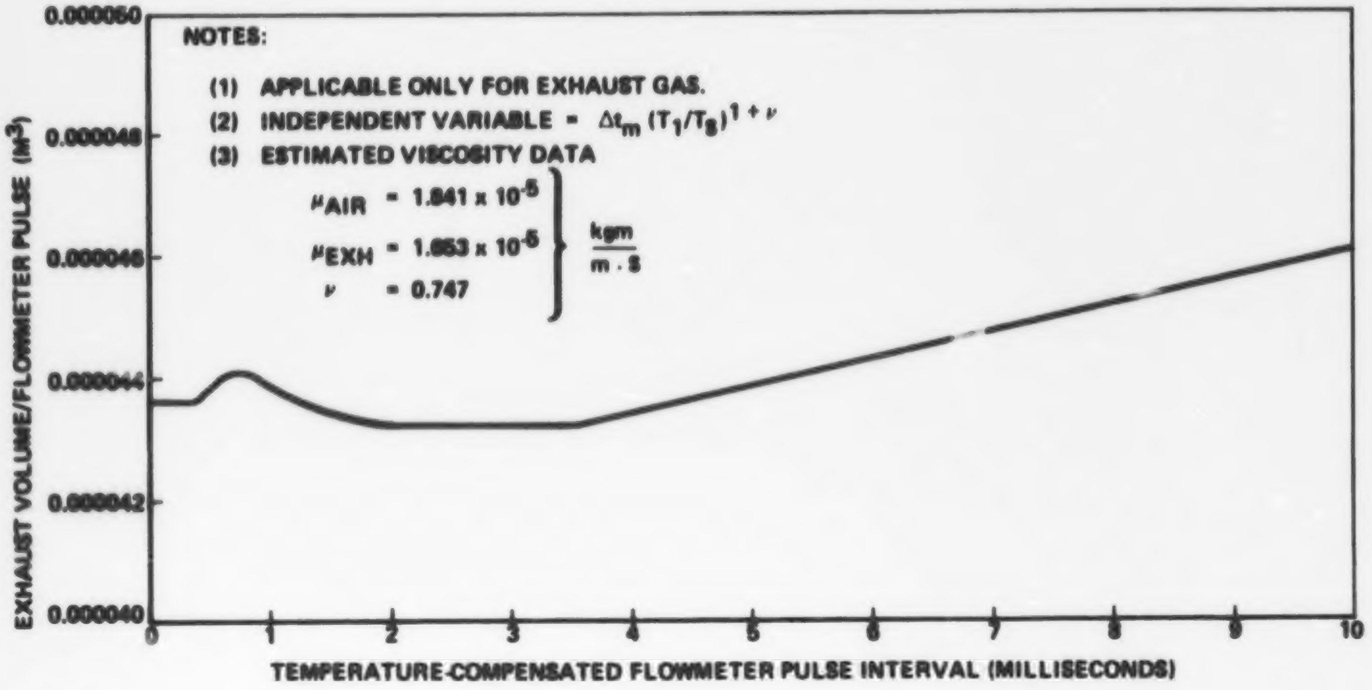

Figure 1. Exhaust flowmeter calibration function

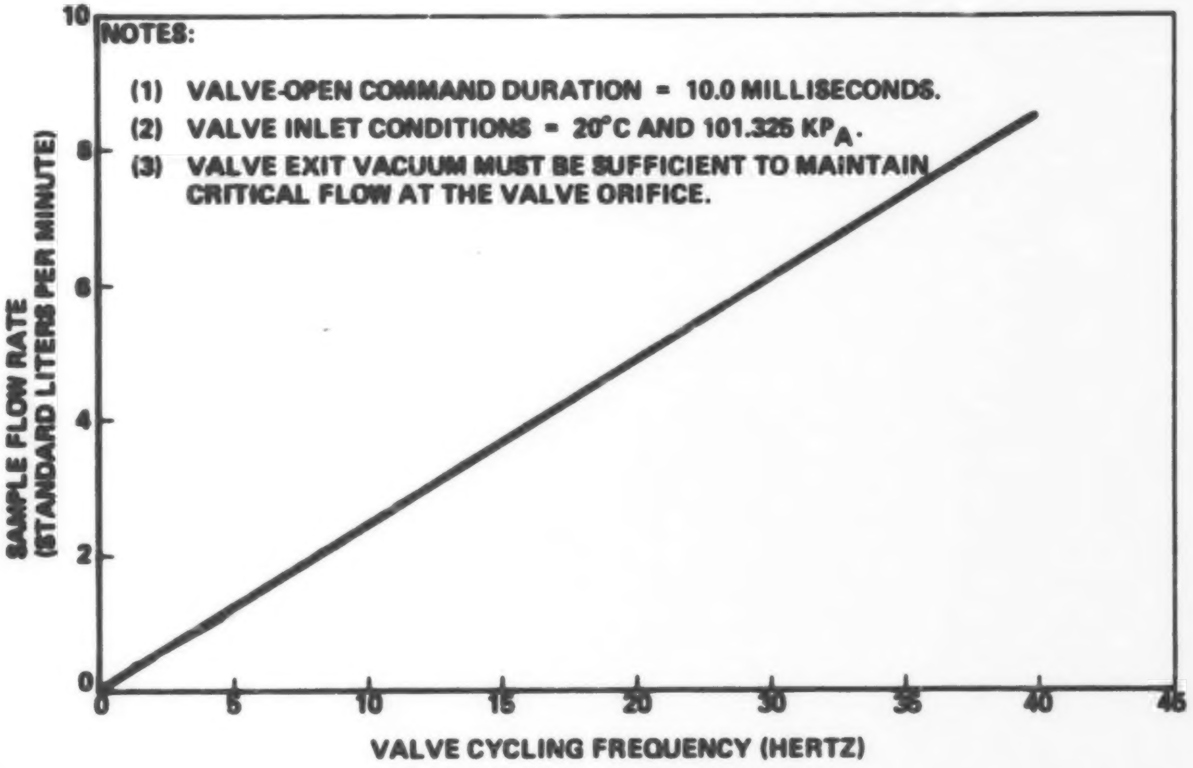

Figure 2. Sample flow control valve calibration function

(e) Withstand repeated exposure to unfiltered exhaust gas at inlet temperatures up to 450°C without degradation in performance.

4.3 Instrumentation

The device shall incorporate the following instrumentation as required to perform the exhaust and sample flow metering functions:

(a) Exhaust pressure - 0 to 103.421 KP_a absolute pressure transducer of the strain-gage diaphragm type with ±1/2 percent overall accuracy.

(b) Exhaust and sample valve inlet temperatures - platinum wire resistance temperature sensors with ±1/4 percent accuracy (not including error due to nonlinearity) over the range from 5°C to 450°C.

4.4 Signal Processing Electronics

The device shall employ analog and digital signal processing electronics to perform the following functions:

(a) Receive the exhaust flowmeter, pressure transducer, and temperature sensor signals and determine the cumulative exhaust volume at the standard conditions of 20°C and 101.325 KP_a for display on the control panel.

(b) Provide valve-open and valve-close command signals to the sample flow control valve such that the mass flow rate of sample is a constant fraction of the exhaust mass flow rate.

(c) Provide output signals of exhaust volume and mass flow rates, exhaust pressure and temperature, sample valve inlet temperature, and the valve open/close commands.

The following equations shall be implemented in the signal processing electronics (nomenclature per Table A):

(a) Exhaust flowmeter volume/pulse -

$$\Delta ACF = \text{Function of } \Delta T_{meter} \, (T_1/T_S)^{1+m}$$

TABLE A

NOMENCLATURE FOR SIGNAL PROCESSING EQUATIONS

ΔACF = Exhaust volume per flowmeter pulse (m^3)

$\Delta\tau_{meter}$ = Exhaust flowmeter pulse duration (seconds)

T_1 = Exhaust gas temperature at flowmeter (°K)

T_S = Standard temperature = 273.16°K

m = Exhaust gas viscosity temperature exponent

ΔSCF = Exhaust mass per flowmeter pulse (m^3 at 20°C and 101.325 KP_a)

P_1 = Exhaust gas pressure at flowmeter (KP_a, absolute)

P_S = Standard pressure = 101.325 KP_a

SCF = Cumulative exhaust mass over the test interval

$\sum_{TEST}$ $\sim$ Summation of flowmeter pulses over the test interval

τ_{cycle} = Sample flow control valve cycle time, i.e., between valve-open commands (seconds)

$\sum_{CYCLE}$ $\sim$ Summation of flowmeter pulses over the valve cycle time

K = Sample flow proportionality constant (ppk)

$(SCFH)_m$ = Sample valve full-open flow rate at standard conditions (m^3/hr)

TABLE A (Continued)

NOMENCLATURE FOR SIGNAL PROCESSING EQUATIONS

T_2 = Gas temperature at sample valve inlet (°K)

q_{leak} = Ratio of leakage/full-open sample flow during valve-closed interval

q_{open} = Ratio of average/full-open sample flow during valve-open interval

$\Delta\tau_{open}$ = Sample valve open time, i.e., between valve-open and valve-close commands (seconds).

ACFM = Exhaust volume flow rate (m^3/hr)

SCFM = Exhaust mass flow rate (m^3/hr at standard conditions)

(b) Exhaust flowmeter mass/pulse -

$$\Delta SCF = \left(\frac{P_1}{P_S}\right)\left(\frac{T_S}{T_1}\right)\Delta ACF$$

(c) Cumulative exhaust mass -

$$SCF = \sum_{TEST} \Delta SCF$$

(d) Sample flow control valve cycle time -

$$\tau_{cycle} = \sum_{CYCLE} \Delta\tau_{meter}$$

With the summation limit determined by the criterion:

$$\sum_{CYCLE} \left[3.6K \frac{\Delta ACF}{(SCFH)_m} \left(\frac{T_S}{T_1}\right)\left(\frac{T_2}{T_S}\right)^{1/2} - q_{leak}\,\Delta\tau_{meter}\right]$$

$$\geq \Delta T_{open}\,(q_{open} - q_{leak})$$

(e) Exhaust volume and mass flow rates -

$$ACFM = 3600\ \Delta ACF/\Delta\tau_{meter}$$

$$SCFM = 3600\ \Delta SCF/\Delta\tau_{meter}$$

The signal processsing electronics shall include compensation for input signal nonlinearities and shall be implemented such that the overall accuracy requirements of the device are satisfied, with due consideration for the accuracy limitations of the exhaust flowmeter, sample flow control valve, and instrumentation.

4.5 Exhaust Flow Conditioning

The device shall include an exhaust heat exchanger and plenum tank located between the point of sample extraction and the exhaust flowmeter. The heat exchanger shall be an open cycle water/exhaust type requiring less than 40 lpm ambient temperature cooling water to maintain the exhaust temperature below 65°C at the flowmeter. The plenum tank shall have sufficient volume to eliminate acoustic interference at the flowmeter.

APPENDIX B

PROPORTIONAL SAMPLER EVALUATION TEST PLAN

I. OBJECTIVE AND SCOPE

The objective of the Proportional Sampler evaluation testing is to verify the accuracy and repeatability of the device. The testing is to be conducted at the EPA Research Triangle Park facility. The device will be installed in series with a CVS in an emissions test cell. A referee engine will be driven through the LA-4-S-3 driving schedule. A minimum of 10 such tests will be performed. The mass emissions of CO_2, CO, HC, and NO_x will be determined from both the Proportional Sampler and the CVS for each test. Statistical tests will be performed with these data to demonstrate the accuracy and repeatability of the Proportional Sampler data in comparison to the EPA CVS.

The purpose of this test plan is to define the procedural requirements for the installation, calibration, test and data analysis phases of the evaluation.

II. INSTALLATION

The evaluation test setup is shown schematically in Figure 1. Installation of the Proportional Sampler in the test cell should proceed in accordance with detailed Operating and Maintenance Instructions. The steps involved include:

(1) Tie-down of console floor jacks.

(2) Attachment of facility ducting from engine exhaust and to CVS inlet.

(3) Attachment of sample transfer and condensate trap drain lines.

(4) Filling of the refrigerated water bath.

(5) Hookup to facility power.

(6) Checkout of console adjustments.

(7) Checkout of console functions.

(8) Attachment of the heat exchanger and plenum tank to the proportional sampler ducts.

(9) Completion of system leak checks.

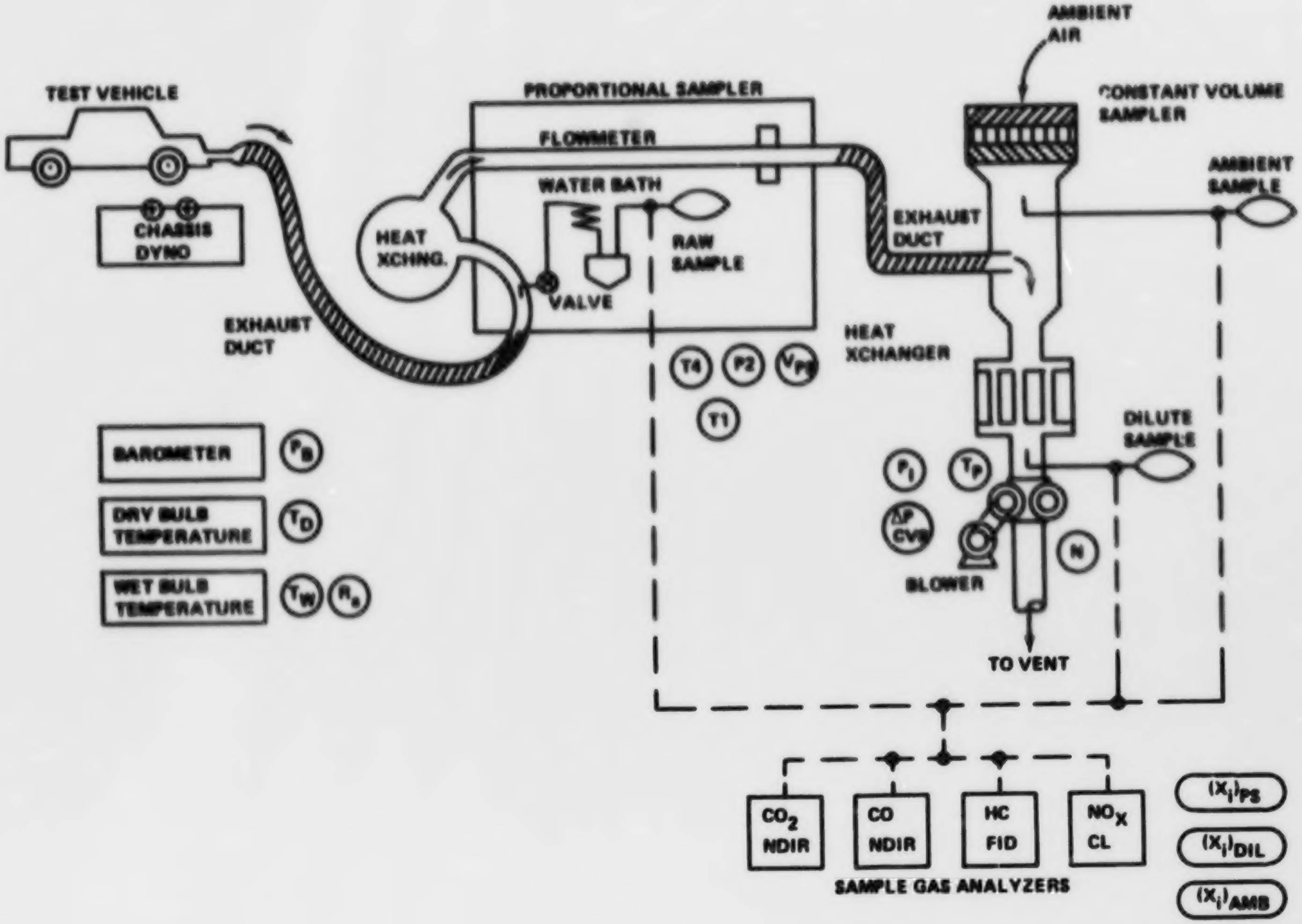
TEST VEHICLE
CHASSIS DYNO
EXHAUST DUCT
PROPORTIONAL SAMPLER
FLOWMETER
WATER BATH
HEAT XCHNG.
VALVE
RAW SAMPLE
T4
P2
V_{PS}
T1
HEAT XCHANGER
EXHAUST DUCT
AMBIENT AIR
CONSTANT VOLUME SAMPLER
AMBIENT SAMPLE
DILUTE SAMPLE
P_I
T_P
ΔP CVS
N
BLOWER
TO VENT
BAROMETER
P_B
DRY BULB TEMPERATURE
T_D
WET BULB TEMPERATURE
T_W
R_s
CO_2 NDIR
CO NDIR
HC FID
NO_X CL
SAMPLE GAS ANALYZERS
$(X_i)_{PS}$
$(X_i)_{DIL}$
$(X_i)_{AMB}$

Figure 1. Proportional sampler evaluation test setup

In addition to these basic steps, the entire CVS and sample analysis plumbing should be thoroughly leak checked. All sample lines which are under vacuum must be made leak free so that no uncontrolled dilution of sample gas can occur.

If desired, the vehicle driver can be provided with a remote start switch from the Proportional Sampler control panel. This may simplify the overall synchronization of the test between the vehicle, Proportional Sampler, and CVS.

III. CALIBRATIONS

All test equipment calibrations should be checked prior to the series of evaluation tests. The Proportional Sampler will be fully calibrated prior to shipment to the EPA. It will only be necessary to verify the digital switch settings in the signal processing electronics, and check the pressure and temperature sensor calibrations. The remaining calibrations of principal importance are the CVS blower, the sample gas analyzers, and the test fuel. The requirements for these are summarized in the following paragraphs.

A. CVS Blower

It is understood that the CVS to be used in the evaluation tests will be a conventional Rootes blower type. The volume per blower revolution should be accurately determined using a laminar flow element (LFE) in accordance with existing EPA procedures. (Reference Federal Register, Vol. 38, No. 124, Appendix III, Thursday, June 28, 1973, pp. 17167-8.) Since even the use of an LFE does not guarantee calibration to a uniform standard between the Proportional Sampler and the CVS, it is recommended that the CVS blower calibration be performed using both the EPA and the Aeronutronic LFE's. The Aeronutronic LFE will be shipped along with the Proportional Sampler for this purpose. This dual calibration of the EPA CVS will identify any differences in the two flow standards prior to the evaluation tests. Resolution of such differences can then be made independent of the evaluation test comparisons between the Proportional Sampler and CVS.

Calibration of the other CVS readouts (revolution counters, pressure and temperature recorders) should also be completed. By assuring the CVS accuracy, any differences between the Proportional Sampler and CVS specie masses can be isolated to the Proportional Sampler.

B. Sample Gas Analyzers

The CO_2, CO, NO_x and FID analyzers should be completely recalibrated prior to the evaluation tests. The Proportional Sampler raw sample and CVS dilute sample will probably require different analyzer ranges. This can lead to spurious differences in the specie masses unless each range utilized is calibrated separately. The calibration gases should be characterized to within ± 1 percent of measured concentrations. The existing EPA calibration procedures should be employed.

IV. TEST OPERATIONS

Although the evaluation test setup is designed to minimize the impact of vehicle, driver, and test cycle variabilities, it is recommended that the series of 10 tests employ a single vehicle, driver, and driving cycle. The vehicle should have a V-8 engine with approximately 5.75 liter displacement. The driving cycle should be the LA-4-S-3 implemented with a hot start (i.e., temperature stabilized engine).

The following paragraphs contain recommendations for the scope of the various test operations. Further detailed test procedures are left to the discretion of EPA personnel.

A. Cell Preparation

The pre-test preparations include the following general tasks for the Proportional Sampler, CVS, and vehicle:

(1) Turn on Proportional Sampler console power.

(2) Turn on CVS power and blower.

(3) Purge and evacuate all sample collection bags.

(4) Replace sample filter elements.

(5) Set heat exchanger water flow at desired value.

(6) Fuel vehicle and run the engine to stabilize the temperature, and warm up the dynamometer.

(7) Perform Proportional Sampler function check, including sample valve power.

(8) Set test interval and exhaust flow selector switches on Proportional Sampler control panel to desired values.

(9) Turn on Proportional Sampler and CVS sample pumps.

(10) Check instrumentation hookups and readings for CVS and Proportional Sampler.

B. Pre-Test Data Acquisition

The pre-test data to be recorded include the following:

(1) Barometric pressure (P_B).

(2) Ambient dry-bulb temperature (T_D).

C. Test Sequence

The test sequence should proceed in accordance with normal EPA procedure. The "start test" signal should be input to the Proportional Sampler coincident with the CVS. The Proportional Sampler will automatically enter the end-of-test mode in accordance with the previously selected test intervals.

D. Test Data Acquisition

During the actual test the following data should be recorded:

(1) Proportional Sampler water bath temperature (T4).

(2) Proportional Sampler sample line vacuum (P2).

(3) Exhaust Temperature (T_1) at the flowmeter.

(4) CVS blower inlet vacuum (P_I).

(5) CVS blower differential pressure (ΔP_{CVS}).

(6) CVS blower inlet temperature (T_P).

E. Sample Analyses

After completion of the test, the bag samples should be analyzed for CO_2, CO, HC (FID), and NO_x (CL) in the following order:

(1) Proportional Sampler raw exhaust sample.

(2) CVS dilute exhaust sample.

(3) CVS ambient air sample.

The analyzers should be zeroed, spanned, and zero-checked before and after each sample. Span gases should have ±1 percent relative accuracies.

F. Post-Test Data Acquisition

After the test the following data should be recorded:

(1) Proportional Sampler cumulative exhaust volume readout (V_{PS}).

(2) CVS blower cumulative revolutions (N).

$$\left.\begin{array}{ll}\text{(3)} & \text{Raw exhaust sample concentrations } (X_i)'_{PS} \\ \text{(4)} & \text{Dilute exhaust sample concentrations } (X_i)_{DIL} \\ \text{(5)} & \text{Ambient air sample concentrations } (X_i)_{AMB}\end{array}\right\} i = CO_2,\ CO,\ HC,\ NO_x$$

V. DATA ANALYSIS

A. Proportional Sampler Specie Masses

The masses of CO_2, CO, HC, and NO_x emitted by the vehicle over the LA-4-S-3 test, as measured by the Proportional Sampler, should be calculated using the following equations:

(1) Specie masses

$$(CO_2)_{PS} = \rho_{CO_2} V_{PS} (X_{CO_2})_{PS}$$

$$(CO)_{PS} = \rho_{CO} V_{PS} (X_{CO})_{PS}$$

$$(HC)_{PS} = \rho_{HC} V_{PS} (X_{HC})_{PS}$$

$$(NO_x)_{PS} = \rho_{NO_2} V_{PS} (X_{NO_x})_{PS}$$

where: ρ_{CO_2} = CO_2 density at standard conditions (760 mm Hg and 68°F)

= 1.831 kgm/m^3

ρ_{CO} = CO density at standard conditions

= 1.164 kgm/m^3

ρ_{HC} = Hydrocarbon density at standard conditions

= 0.577 kgm/m^3

ρ_{NO_2} = NO_2 density at standard conditions

= 1.913 kgm/m^3

V_{PS} = Cumulative exhaust volume at standard conditions as read at the Proportional Sampler control panel (cubic meters)

$(X_i)_{PS}$ = Volume fraction of the ith specie ($i = CO_2$, CO, HC, NO_x) in the raw exhaust sample, corrected for water vapor removal

(2) Specie volume fractions

$$(X_i)_{PS} = (X_i)'_{PS}\ [1-(X_{H_2O})_{PS}]/[1-(X_{H_2O})'_{PS}]$$

where: $(X)'_{PS}$ = Volume fraction of the ith specie in the raw exhaust sample, as measured by the gas analyzers

$(X_{H_2O})_{PS}$ = Volume fraction of water vapor in the cooled exhaust, as calculated below

$(X_{H_2O})'_{PS}$ = Volume fraction of water vapor in the partially dried raw exhaust sample, as calculated below

(3) Cooled exhaust water vapor volume fraction

$$(X_{H_2O})_{PS} = \frac{(SVP)_{T1}}{P_B}$$

where: $(SVP)_{T1}$ = Saturated vapor pressure at the average gas temperature at the exhaust flowmeter kP_a

P_B = Barometric pressure kP_a

and where the temperature T1 may be read out at the proportional sampler control panel.

(4) Sampler water vapor volume fraction

$$(X_{H_2O})'_{PS} = \frac{(SVP)_{T4}}{P_B - P2}$$

where: $(SVP)_{T4}$ = Saturated vapor pressure at the refrigerated water bath temperature T4 kP_a

P2 = Sample line vacuum kP_a, as indicated at the Proportional Sampler control panel and where the temperature T4 is indicated at the Proportional Sampler control panel.

B. CVS Specie Masses

The reference masses of CO_2, CO, HC, and NO_x emitted by the vehicle over the LA-4-S-3 test, as measured by the CVS, should be calculated using the following equations:

(1) Specie masses

$$(CO_2)_{CVS} = \rho_{CO_2} \, V_{CVS} \, (X_{CO_2})_{CVS}$$

$$(CO)_{CVS} = \rho_{CO} \, V_{CVS} \, (X_{CO})_{CVS}$$

$$(HC)_{CVS} = \rho_{HC} \, V_{CVS} \, (X_{HC})_{CVS}$$

$$(NO_x)_{CVS} = \rho_{NO_2} \, V_{CVS} \, (X_{NO_x})_{CVS}$$

where: V_{CVS} = Cumulative dilute exhaust volume (cubic meters), corrected to standard conditions of 101.325 kP_a and 20°C

$(X_i)_{CVS}$ = Volume fraction of the ith specie in the dilute exhaust sample, corrected for ambient concentrations

(2) Cumulative dilute exhaust volume

$$V_{CVS} = V_o \cdot N \cdot \frac{(P_B \quad P_1)\ 293.16}{101.325\ (T_P + 273.16)}$$

where: V_o = Volume of gas pumped per revolution of the CVS blower (cubic meters), as determined from the blower calibration curve for the measured average differential pressure ΔP_{CVS} across the blower

N = Number of CVS blower revolutions during the test, as measured by the revolution counter

P_I = Vacuum at the inlet to the CVS blower kP_a, averaged over the test

T_P = Temperature of dilute exhaust at the CVS blower inlet °C, averaged over the test

(3) Specie volume fractions

$$(X_i)_{CVS} = (X_i)_{DIL} - (X_i)_{AMB}\left(1 - \frac{1}{DF}\right)$$

where: $(X_i)_{DIL}$ = Volume fraction of the ith specie in the dilute exhaust sample, as measured by the gas analyzers

$(X_i)_{AMB}$ = Volume fraction of the ith specie in the ambient air sample, as measured by the gas analyzers

DF = CVS dilution factor, as calculated below

(4) CVS dilution factor

$$DF = \frac{(X_{CO_2})_{PS}+(X_{CO})_{PS}+(X_{HC})_{PS}-(X_{CO_2})_{AMB}-(X_{CO})_{AMB}-(X_{HC})_{AMB}}{(X_{CO_2})_{DIL}+(X_{CO})_{DIL}+(X_{HC})_{DIL}-(X_{CO_2})_{AMB}-(X_{CO})_{AMB}-(X_{HC})_{AMB}}$$

C. Statistical Analysis

The Proportional Sampler accuracy and repeatability should be determined through statistical analysis of at least 10 comparison tests (i.e., trials), with the EPA CVS. The random variables should be defined as:

$$\Delta_{CO_2} \equiv \frac{(CO_2)_{PS} - (CO_2)_{CVS}}{(CO_2)_{CVS}}$$

$$\Delta_{CO} \equiv \frac{(CO)_{PS} - (CO)_{CVS}}{(CO)_{CVS}}$$

$$\Delta_{HC} \equiv \frac{(HC)_{PS} - (HC)_{CVS}}{(HC)_{CVS}}$$

$$\Delta_{NO_x} \equiv \frac{(NO_x)_{PS} - (NO_x)_{CVS}}{(NO_x)_{CVS}}$$

Then for each specie the mean and standard deviation should be calculated using the following:

$$\overline{\Delta}_i = \sum_{j=1,n} (\Delta_i)_j/n$$

$$S_i = \{ \sum_{j=1,n} [(\Delta_i)_j - \overline{\Delta}_i]^2/(n-1)\}^{1/2}$$

where: $\overline{\Delta}_i$ = Mean difference for ith specie

Δ_i = Random variable for the ith specie

n = Number of trials

j = Summation index

S_i = Standard deviation for ith specie

The desired value of the mean differences is zero. The limits of systematic (i.e., non-random) inaccuracy for the specie masses should be determined using the T distribution for small sample tests. With a probability of 0.9 the absolute value of the systematic error will be less than:

$$\varepsilon_i = |\overline{\Delta}_i| + \frac{T_{0.9}\, S_i}{\sqrt{n}}$$

where: $|\overline{\Delta}_i|$ = Absolute value of the mean difference for the ith specie

$T_{0.9}$ = Value of the T statistic up to which the area under the T distribution is 0.9.

= 1.383 for 9 degrees of freedom (10 trials)

The limits of random inaccuracy (i.e., nonrepeatability) for the specie masses should be determined using the chi-squared distribution. With a probability of 0.9 the absolute value of the nonrepeatability will be less than:

$$3\sigma_i = 3 \,.\, S_i \left(\frac{n-1}{\chi^2_{0.9}}\right)^{1/2}$$

where: $\chi^2_{0.9}$ = Value of the chi-squared statistic beyond which the area under the chi-squared distribution is 0.9.

= 4.168 for 9 degrees of freedom (10 trials)

The performance goals for the Proportional Sampler are (1) accuracy within ±3 percent and (2) repeatability within ±5 percent. These goals correspond to the following criteria, respectively:

$$\varepsilon_i \leq 0.03$$

$$3\sigma_i \leq 0.05$$

which for 10 trails imply the following approximate limits for the means and standard deviations:

$$|\bar{\Delta}_i| \leq 0.0250$$

$$s_i \leq 0.0113$$

Should these goals not be met for the group of 10 trails, additional diagnostic testing could be performed. For example, if the mean differences are uniformly larger than desired for all species, this would indicate an erroneous flowmeter signal. This discrepancy could be due to the flowmeter calibration, water vapor removal correction, or inadequate suppression of pressure fluctuations at the flowmeter.

A second example would be acceptable accuracy for the CO_2 specie, but poor accuracy for the CO, HC, and NO_x species. This would indicate an adequate flowmeter signal, but an erroneous sample proportionality. Additional testing under steady state conditions would then be desired to determine if dynamic distortion was the cause of the inaccuracy.

A third example would be acceptable accuracy for CO_2 and CO, but not for HC or NO_x. This would indicate acceptable flow-metering and sample proportioning accuracies, but would reveal limitations in the handling of raw exhaust samples. Inaccurate or nonrepeatable HC masses would indicate hang-up in the sample plumbing. It might be possible to further isolate this problem using a methane analyzer. Comparisons of methane mass (if of significant magnitude relative to the total HC mass) could verify the Proportional Sampler basic accuracy since methane is not subject to hang-up.

Inaccurate or nonrepeatable NO_x masses would indicate either loss of NO_x in the condensate trap, or an increased instability of NO_x species at concentrations typical of raw exhaust. Tests to isolate these possibilities might include a pH measurement of the water from the condensate trap and measurement of NO_x decay rate in the raw exhaust sample.

Once satisfactory accuracy and repeatability have been established for the Proportional Sampler, the testing may be expanded to include cold starts and alternate vehicles.